# Analyzing Vibrotactile Feedback Strategies Across Diverse Digital Musical Instruments

*Oren D. Ronen*

Music Technology Area
Schulich School of Music
McGill University
Montreal, Canada

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# Abstract

Digital Musical Instruments (DMIs) often lack the rich haptic feedback that defines the experience of playing acoustic instruments, therefore creating an experiential gap for performers. This thesis investigates how vibrotactile feedback can be strategically designed to bridge this gap, exploring how the fundamental characteristics of a DMI influence the conceptualization and implementation of haptic feedback. To address this question, the Sonic Touch Toolkit was developed as a flexible platform for rapid vibrotactile prototyping within Max/MSP. A series of exploratory workshops were conducted where musicians and designers used this toolkit to add haptic feedback to three structurally diverse DMIs: the AKAI MPK Mini (discrete, keyboard-style controls), the Linnstrument (a grid-based multidimensional polyphonic controller), and the T-Stick (a sensor-rich gestural controller). These workshops revealed a common design pattern: for DMIs characterized by discrete controls and separable interaction dynamics, such as the AKAI keyboard, participants predominantly designed inherent feedback to enhance the physical feel of the gesture and create a more embodied connection. In contrast, for DMIs with multi-dimensional, integrated controls like the Linnstrument and T-Stick, participants strongly favored augmented feedback, using informational cues to aid sensor navigation, improve gestural accuracy, and provide awareness of the system's internal state. This research contributes a framework that links DMI interaction paradigms to specific vibrotactile design strategies, offering insights for the future design of more expressive and engaging digital musical instruments.

# Resumé

Les instruments de musique numériques (IMN) sont souvent dépourvus de la riche rétroaction haptique qui caractérise l'expérience de jeu des instruments acoustiques, créant ainsi un écart expérientiel pour les interprètes. Cette thèse examine comment la rétroaction vibrotactile peut être conçue de manière stratégique pour combler cet écart, en explorant l'influence des caractéristiques fondamentales d'un IMN sur la conceptualisation et la mise en œuvre de la rétroaction haptique. Pour répondre à cette question, la trousse d'outils Sonic Touch a été développée comme une plateforme flexible pour le prototypage rapide vibrotactile dans l'environnement Max/MSP. Une série d'ateliers exploratoires ont été menés, au cours desquels des musiciens et des concepteurs ont utilisé cette trousse pour ajouter de la rétroaction haptique à trois IMN structurellement différents: l'AKAI MPK Mini (contrôles discrets de type clavier), le Linnstrument (un contrôleur polyphonique multidimensionnel à grille) et le T-Stick (un contrôleur gestuel riche en capteurs). Ces ateliers ont révélé un patron de conception commun : pour les IMN caractérisés par des contrôles discrets et des dynamiques d'interaction séparables, comme le clavier AKAI, les participants ont majoritairement conçu une rétroaction inhérente pour améliorer la sensation physique du geste et créer une connexion plus incarnée. En revanche, pour les IMN dotés de contrôles multidimensionnels et intégrés comme le Linnstrument et le T-Stick, les participants ont nettement privilégié la rétroaction augmentée, utilisant des indices informationnels pour faciliter la navigation entre les capteurs, améliorer la précision gestuelle et informer sur l'état interne du système. Cette recherche apporte un cadre qui établit un lien entre les paradigmes d'interaction des IMN et des stratégies de conception vibrotactile spécifiques, offrant ainsi des pistes pour la conception future d'instruments de musique numériques plus expressifs et engageants.

# Acknowledgements

I'd like to thank my supervisor Marcelo M. Wanderley for his guidance, wisdom, and humour throughout this process, and for making me feel welcome in the program. To all my mates I made along the way, cheers for all the good times, both in the lab and outside (at Piknic). This work was supported in part by the National Sciences and Engineering Research Council of Canada (NSERC) awarded to Professor Wanderley, and by the Center for Interdisciplinary Research in Music Media and Technology (CIRMMT). Finally, special thanks to my parents and my grandparents for their love and support, long-distance calls, and for always encouraging me to follow my passions.

# Chapter 1

# Introduction

The body contains a rich system of receptors in the skin that inform us of our interaction with the external environment. For a musician, these sensors in the fingertips and lips, for instance the Meissner corpuscles, are vital in providing valuable information about the state of their instrument. From the subtle vibrations a guitarist feels through their fingertips as they press a guitar string to the fretboard, to the focused vibration a trumpeter's lips against the mouthpiece to achieve an upper-register note, the relationship between musician and instrument can be thought of as a 'coupled system' [1], in which the musician is constantly predicting and responding to haptic signals whilst playing.

In recent decades, the advancement of Digital Musical Instruments (DMIs) has revolutionized the sonic landscape, offering a near limitless palette of synthesis and mapping combinations. Digital instruments are no longer bound by the physical limitations of acoustic sound production; a single button press can trigger a rich symphony of sounds. However, this physical decoupling has come at a cost of this coupled haptic system. Many DMIs, from commercial keyboard controllers to touch-screen interfaces, lack the 'energy exchange' that makes acoustic interaction so compelling. This experiential gap can leave the performer feeling detached, and is often cited as the reason DMIs have not achieved the 'expressiveness' of acoustic counterparts [2].

To help bridge this gap, this thesis investigates how vibrotactile feedback can be strategically designed and implemented to restore a meaningful sense of touch to DMIs. The goal is not simply to mimic the feel of acoustic instruments, but to explore how haptics can unlock new modes of control, communication, and creative expression unique to the digital domain. The 'experiential gap' this thesis addresses is detailed in literature on embodied cognition and performance-instrument coupling. Frameworks such as those by O'Modhrain & Gillespie [1] and Cadoz [3] argue that the physical energy exchange between acoustic instruments and performers is not merely preferential, but fundamental to musical expression and skill acquisition. This thesis builds on that perspective, investigating vibrotactile feedback as a crucial channel for restoring a meaningful sense of bidirectional interaction with a DMI.

## 1.1 Thesis Overview

This research employs an exploratory design approach to investigate the addition of vibrotactile feedback across a diverse set of DMIs, providing insights into how different designers conceptualize and implement haptic feedback for various musical devices. This methodology follows a design ethnography approach [4], which studies the process of design itself to understand how designers conceptualize and solve creative problems. Through a series of workshops, we observe how designers and musicians conceptualize and implement haptic feedback for various musical devices. The goal is to derive device-specific considerations into generalizable strategies for both device and haptic feedback design. We keep the aim of the haptic feedback as open as possible, asking participants to design vibrotactile feedback that simply "enhances the interaction with the DMI", using a custom toolkit we developed specifically for this application known as the Sonic Touch Toolkit. Through these exploratory workshops, we hope to answer both our primary and secondary research questions:

RQ1: How do DMI characteristics influence the design requirements and opportunities for custom vibrotactile feedback?

RQ2: Can these decisions be generalized to create a set of design recommendations for future

DMI designers hoping to incorporate vibrotactile feedback into their instruments?

**Chapter 2** details a literature review on DMIs exhibiting vibrotactile feedback in the International Conference on New Interfaces for Musical Expression (NIME). DMIs will be categorized in terms of the types of vibrotactile signals displayed.

**Chapter 3** details the design, motivation, and functionality of the Sonic Touch Toolkit. It also presents a case study illustrating how the toolkit can be used to implement vibrotactile feedback strategies on a commercial MIDI controller.

**Chapter 4** details the methodology of our exploratory investigation. This includes the rationale for selecting three distinct DMIs (the AKAI MPK Mini, the Linnstrument, and the T-Stick), the process of augmenting them with vibrotactile capabilities, and the structure of the participant-led design sessions.

**Chapter 5** presents the results from the workshops. It analyzes participants' design approaches, classifying the created feedback strategies and examining how the physical and interactive characteristics of each DMI influenced their choices.

**Chapter 6** discusses the findings in a broader context, proposing a set of generalizable design strategies. It explores the experiential value of vibrotactile feedback, the influence of DMI characteristics on feedback design, and specific choices in parameterization and mapping.

**Chapter 7** concludes the thesis, summarizing the key contributions and suggesting directions for future research in the design of expressive and engaging digital musical instruments.

# Chapter 2

# Background

Early research in the 1990s and early 2000s into vibrotactile feedback applications for DMIs proved its utility. Chafe [5] found that vibrotactile feedback to the fingertips corresponding to lip tension improved both sound quality and controllability of a physical model brass instrument. In open air music controllers, tactile cues were used to provide hand displacement detail for the instrumented Mattel Powerglove [6], and by the VR/TX environment by Rovan & Hayward [7] to indicate switching program states and zone border crossings.

## 2.1 Feedback Topologies

Given the variety of ways vibrotactile feedback can be implemented in DMIs, it is useful to discuss ways to categorize the feedback. Rovan & Hayward presented a vibrotactile classification system, defining feedback as either time dependent or space dependent. Time dependent feedback corresponded to discrete events, such as signaling a program state change with short haptic pulse. Space dependent feedback related the feedback to the user's movements with modulations and continuous haptic textures. Whilst this classification worked well their open-air controller system, it is difficult to define space dependent feedback for physical, handheld, or tabletop DMIs.

Giordano [8] presented a vibrotactile taxonomy comprising of three categories: tactile notification, tactile translation, and tactile synthesis. Similar to Rovan & Hayward's time-dependent definition of feedback, tactile notification intended to notify the user about the surrounding environment or interaction with a system. Tactile translation is split into two classes; sensory substitution, which involves translating information from one sensory modality (e.g., vision or hearing) to the sense of touch, and tactile rendering, which involves capturing the vibrotactile characteristics of one physical device (e.g. an acoustic guitar) and reproducing them on a different interface. The final category, tactile synthesis, focuses on creating a compositional language based exclusively on the sense of touch.

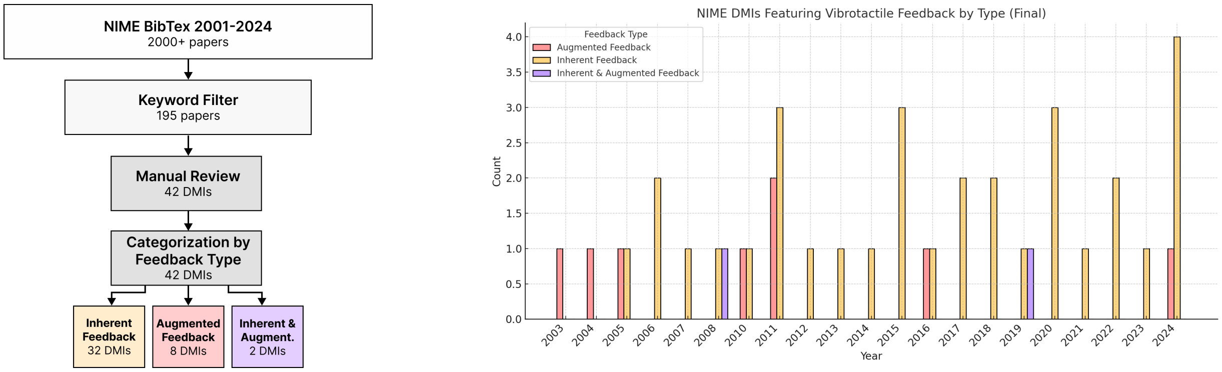
While Giordano's taxonomy focuses on the communicative function of the feedback, other frameworks classify it based on its relationship to the performer's task. Birnbaum [9] borrows concepts from motor control and learning research [10] to propose a topology that takes into account the relationship between the performer and the instrument. This topology categorized vibrotactile feedback as either *inherent* or *augmented*. Inherent vibrotactile feedback is perceived as task-intrinsic, i.e. it naturally arises from the task itself such as plucking the string on a guitar and feeling the corresponding vibrations through the body of the instrument. This type of feedback could be described as "natural" or part of the instrument itself. When it comes to DMIs however, it can be difficult to determine what counts as inherent feedback as there is no natural acoustic reference. Birnbaum resolves this by defining inherent feedback which conforms to the preexisting cognitive model of acoustic vibrotactile feedback. For instance, vibrotactile feedback on a digital wind instrument that mimicked the natural vibrations of its acoustic counterpart would be regarded as inherent feedback. However, this concept extends beyond what Giordano terms 'translation', it could equally involve feeling the vibrations of an FM synthesis model transmitted through the DMI's physical structure. Augmented vibrotactile feedback provides additional information beyond, or not intrinsic to, the musical task itself. For example, score-level cues such as feeling the tempo of an accompaniment track through the body of the instrument would be classified as augmented feedback as it does not relate directly to musician's interaction with the instrument.

The *inherent*/*augmented* classification system seems well-suited when it comes to further analysis of vibrotactile feedback in DMIs as it examines how the feedback integrates with the musician's experience and expectations. If the intention of a DMI designer was to make their instrument feel more like an acoustic instrument, inherent vibrotactile feedback offers a way to achieve this. If the goal was to help a novice learn a new DMI, augmented feedback may be more suitable. With this framework, we can analyze how different DMI designers and musicians approach implementing vibrotactile feedback from an intent perspective, and hopefully by studying different implementation approaches, produce generalizable design strategies for DMIs.

## 2.2 NIME DMIs

The New Interfaces for Musical Expression (NIME) conference was first held in 2001 as a workshop at the ACM Conference on Human Factors in Computing Systems (CHI), and has since been dedicated to presenting new musical interface designs and their artistic performance. As NIME is held annually, we can use it to track trends in technologies used by DMI designers. Specifically, we can get an understanding of if DMI designers have adopted vibrotactile feedback into their creations, and if so, in what way. Whilst we will use NIME proceedings as our primary research source, it is also important to recognize the large body of DMI research that exists before NIME's inception. As Wanderley [11] notes, significant foundational work exists in the International Computer Music Conference and the Computer Music Journal, and early work at ACROE, France, on haptic feedback based on physically modeled systems.

To begin this review, all NIME BibTeX files from 2001 to 2024 were downloaded and filtered on matches of keywords `haptic, haptics, vibrotactile, vibration, tactile` in the BibTeX field data `"Author", "Title", "Year", "Keywords", "Abstract", "Tag", "Url"`. This returned a total of 195 papers. These papers were then manually processed and filtered further based on a) whether papers discussing "haptic" feedback referred to vibrotactile feedback (as opposed to force feedback or other), and b) the vibrotactile feedback was featured in a DMI. Regarding the second point, papers disregarded here included purely perceptual studies (did not feature a DMI), music installations (that featured no physical interaction), or audience feedback



(a) NIME paper review pipeline.

(b) NIME DMIs by vibrotactile type and year.

**Fig. 2.1** NIME literature review process. (a) Paper selection and categorization pipeline. (b) Count of NIME DMIs featuring vibrotactile feedback, categorized by type (Inherent, Augmented, or Both) and year.

devices. This process left 42 papers which featured a vibrotactically enabled DMI. These papers were categorized using Birnbaum's vibrotactile classification, grouping papers with DMIs featuring either *inherent* or *augmented* feedback, or both (Figure 2.1a), and plotted by year (Figure 2.1b).

### Inherent Vibrotactile DMIs

The majority of vibrotactically enabled DMIs at NIME featured inherent vibrotactile feedback (81.0%). Interestingly, there appears to be a spike in the use of inherent vibrotactile feedback every 4-5 years since 2006 (Figure 2.1b). Some example include the Daïs [12], a hand controlled physical bowed string model, of which the user can feel the audio output directly through a voice coil attached to the underside of the pressure plate. The Tingle [13] featured two vibration motors embedded in the body of the handheld controller, with the goal to imitate the feel of an acoustic instrument. The Viblotar [14] was built to examine the effects of vibrotactile feedback on the feel of a digital instrument. It featured two speakers embedded in the body of the instrument, facing outwards to prioritize sound projection. The design contrasts the two former DMIs, which directly fitted an actuator to interaction surface, thus acting as the primary resonator. Users of the Viblotar reported only a marginal improvement in engagement compared to the case when audio was routed to external speakers, and surprisingly a decrease in controllability. This supports a fundamental design trade-off between optimal tactile feedback and sound projection, and corresponds with Chafe's earlier findings which demonstrated that *direct* coupling between the actuator and interaction surface provided most notable control improvements.

### Augmented Vibrotactile DMIs

DMIs that featured augmented vibrotactile feedback were less common (23.8%). The GestoLumina DMI [15] featured haptic rings worn on the fingers, through which the performer could feel rhythmic patterns sent by accompanying musicians wearing the same rings. Both the Soundstone [16], a handheld music controller, and the StickMusic controller [17] similarly used vibrotactile feedback to indicate whether a virtual boundary had been reached. Supporting early vibrotactile encoding recommendations of Rovan & Hayward, tactile feedback indicating the crossing of a virtual surface was shown to improve the controllability and temporal accuracy of an open air controller in [18].

Only two DMIs featured a combination of inherent and augmented vibrotactile feedback. The first is the A20 [19], a multi-channel polyhedron-shaped audio device, in which designers explored either combining the haptic feedback with the corresponding music, or keeping them independent. Second DMI to feature both types of feedback is The Sponge [20]. Researchers explicitly address the implementation of three different mappings to enhance the feel of the instrument, namely "sign-based" to aid the performers spacial localization (augmented), "signal based" which were driven directly by the audio output of the DMI (inherent), and lastly "cue-based" for performance suggestions (augmented). These two DMIs were counted in the totals for both the inherent and augmented categories, hence the percentages presented above do not sum to 100%.

### Vibrotactile Implementation Considerations

It clear that inherent vibrotactile feedback is most popular among DMI designers, with many using it to enhance the *feel* of their instruments, and only a fraction use feedback to improve *control*. One explanation is that inherent feedback is usually easier to implement (Figure 2.2); a simple way to achieve this is by routing the audio synthesis directly to an actuator, generally with minimal

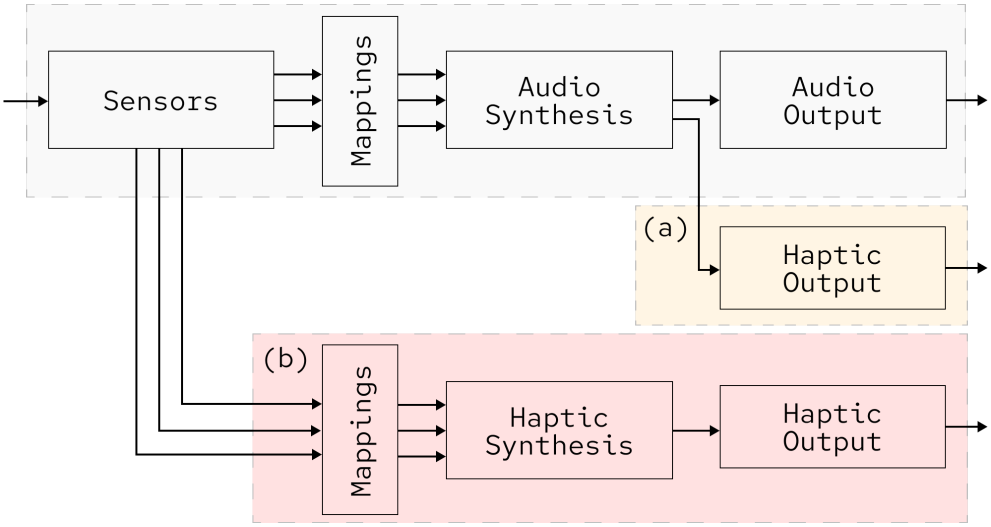


**Fig. 2.2** A comparison between implementing inherent and augmented vibrotactile feedback. Basic instrument design pipeline in gray. A simple way to achieve inherent feedback (a) by routing the audio synthesis directly to a haptic actuator. Augmented feedback (b) requires extra steps of independent tactile mapping and synthesis.

or no audio processing [21, 22, 23]. Even when more complex audio processing is applied to the synthesis signal, such as filtering to within the vibrotactile perception range [24, 25], it doesn't require a "new" tactile signal to be produced. There are considerations to be made regarding the type and placement of the actuator, however there is usually limited to the form factor of the DMI.

To implement augmented feedback on the other hand, a designer needs to first design the haptic effect, which in most cases is separate from the primary audio synthesis. This may be done with the same primary synthesis tool, however in the case that an instrument is built around physically modeled synthesis [5, 12, 26, 27], however relying on the same physically modeled synthesis for the augmented feedback can limit the designer's control over specific haptic parameters. Then follows the non-trivial task of mapping control gestures to vibrotactile feedback. Through attempting to understanding how DMI designers approach the task of making mappings, West [4] described this can often be the most difficult part of the design process due to the overwhelming number of possibilities. Flexibility to change the tactile design and mappings are key here as often it comes down to trial and error to achieve what feels right for a given instrument.

## 2.3 Vibrotactile Tools for DMIs

The analysis of the NIME literature in the previous section reveals that while vibrotactile feedback is a valued feature, its implementation is often limited to the most straightforward method: directly routing the DMI's audio synthesis signal to an actuator. A deeper dive into the NIME proceedings shows that designers leverage a diverse array of software tools to achieve more nuanced and varied vibrotactile experiences, encompassing both inherent and augmented feedback strategies. This section aims to provide an overview and analysis of these existing software tools and environments that are relevant to the design and implementation of vibrotactile feedback for DMIs. These tools range from general-purpose audio programming environments to specialized haptic toolkits and libraries

The landscape of software for vibrotactile feedback in the DMI space is dominated by general purpose audio programming languages and environments, with Max/MSP standing out as frequently used by NIME DMI designers. Designers have employed Max/MSP for directly routing or processing audio to drive actuators for inherent feedback, as seen in the Viblotar where STK-based physical models within Max/MSP generate the audio for embedded speakers [14], or in the Vocal Vibrations project where a Max/MSP patch processes vocal input to drive transducers in the ORB [25]. It is also used for developing custom patches to map gestures to specific vibrotactile events or continuous modulations for augmented feedback such as providing score-following cues via an Arduino controlled by Max/MSP [28], or managing sensor data and feedback signals for "The Sponge" [20]. Furthermore, Max/MSP can act as a central hub in complex systems, exemplified by the PHASE project where it handled sound generation and communicated via OSC with other systems controlling haptics and visuals [29], or in "The Lorentz Lap Brass" for both audio analysis and generating haptic signals [30]. SuperCollider is another favored general purpose audio programming environment, used to generate complex audio signals for inherent feedback in the self-resonating Feedback Cello, where pickup signals are processed and sent back to actuators on the cello body [27]. Additionally, SuperCollider's capacity to run on embedded systems like the iPod Touch was leveraged for the Overtone Fiddle, enabling onboard DSP for its actuated acoustic body [31]. Functional DSP languages like Faust have been used to implement digital models to create inherent vibrotactile feedback, for example on the SpeakerDrum [32] and the Hummellaphone [21] projects. Furthermore, ForceHost [33] is an open-source toolchain built on a modified version of Faust that generates firmware for ESP32, embedding the authoring and rendering of audio and force-feedback haptics.

A range of specialized frameworks and libraries have also emerged outside the NIME community to address specific needs for haptic design. Syntacts [34] offers an open-source C/C++ software and hardware package for controlling large vibrotactor arrays through digital audio interfaces, providing an API and a GUI for synthesizing, sequencing, and spatializing haptic cues. For large scale actuation, the Vibropixels [35] are a modular, self-contained wireless devices designed to support large numbers of receivers by avoiding packet acknowledgment. Similarly, the VibraForge [36] toolkit was designed for on-body specialized vibrotactile feedback with up to 128 actuators, accompanied by a GUI editor and Python/Unity APIs. The TECHTILE toolkit [37] provides an accessible, low-cost entry point for haptic exploration, particularly for education, using a simple microphone, amplifier, and voice-coil setup to capture and replay tactile sensations.

## 2.4 Conclusion

The review of NIME proceedings has revealed a predominant use of inherent vibrotactile feedback, often linked to its simpler implementation over the more complex augmented feedback. Whilst augmented feedback's adoption has been less widespread, partly due to the increased complexity involved in designing distinct haptic signals and mapping them meaningfully to performer actions and musical contexts, it has highlighted benefits from improving DMI controllability, enhancing spatial awareness, and facilitating score-level interoperability. The existing software landscape shows that while general-purpose audio programming environments like Max/MSP are frequently employed by DMI designers for both synthesis and mapping, the implementation of vibrotactile feedback within these environments often results in bespoke, single-use solutions tailored to a specific instrument or haptic effect. This raises the question: is the predominance of inherent feedback primarily a consequence of the available tools and the ease of its implementation, or does the fundamental structure and interaction paradigm of the DMI itself steer designers towards this approach?

To understand how DMI designers conceptualize and implement vibrotactile feedback across various instruments, a more structured approach to observing these design practices is necessary. This requires a tool that can provide a consistent yet flexible platform for exploration, allowing for an investigation into whether DMI structure indeed influences vibrotactile feedback choices when designers are given the same robust capabilities to create either inherent or augmented effects. Developing such a tool is not merely about providing a new utility, but about creating a research instrument to investigate the very design strategies this thesis seeks to uncover.

# Chapter 3

# Sonic Touch Toolkit

## 3.1 Motivation

Given a DMI, how does one approach the task of integrating vibrotactile feedback? First, the instrument must have some way of producing haptic feedback (more details on physical implementation provided in Chapter 4). Given some form of actuator has been selected and installed, the next non-trivial step is to decide on what vibrotactile feedback works for the given instrument. Take a MIDI controller for example, which may have some combination of keys, knobs, pads, sliders, and buttons. What haptic effect would feel "right" when the user presses a pad? An immediate 100ms haptic click? A double click, this time lower in frequency indicating maximum pressure has been reached? A continuous vibration gradually increasing in amplitude corresponding to the pressure of the press? Perhaps all the above. A designer must not consider only the vibrotactile effect in isolation, but also the mapping between the user input (press) to the haptic output (100ms click). The key here is *experimentation.* Max/MSP is used extensively in the DMI design community [38], both for synthesis and mappings. For this reason, it seemed practical to keep the design and prototyping of vibrotactile feedback within the same environment, reducing the need for DMI designers to work across multiple software applications. To address this need for accessible and rapid experimentation, this chapter details the design and functionality of the

Sonic Touch Toolkit, a modular prototyping environment developed for this purpose.

## 3.2 Functionality

The Sonic Touch Toolkit facilitates both the design and mapping of vibrotactile feedback to the performer [39]. The toolkit is built around a modular architecture, with an emphasis on clean and simple UI. Two guiding principles guided the development of the toolkit; simplicity and immediacy.

### Editing Buffer

**Fig. 3.1** Sonic Touch Toolkit - design of vibrotactile effect, showcasing the design modules.

A vibrotactile effect is prototyped within the "Editing Buffer", displaying its waveform in the visual center. The idea is to allow users to refine their haptic designs within a single "workshop space". Within the editing buffer, a vibrotactile effect is defined by a number of meta parameters: haptic event length (milliseconds), amplitude (via the live gain object), number of repetitions, and delay between repetitions. The user is able to select from a number of predefined parameters, or enter custom values. The editing buffer space further features a oscilloscope, spectrum plot, and spectrogram.

The toolkit's current iteration features a total of seven modules, four haptic design modules, and three mapping modules.

### Haptic design modules

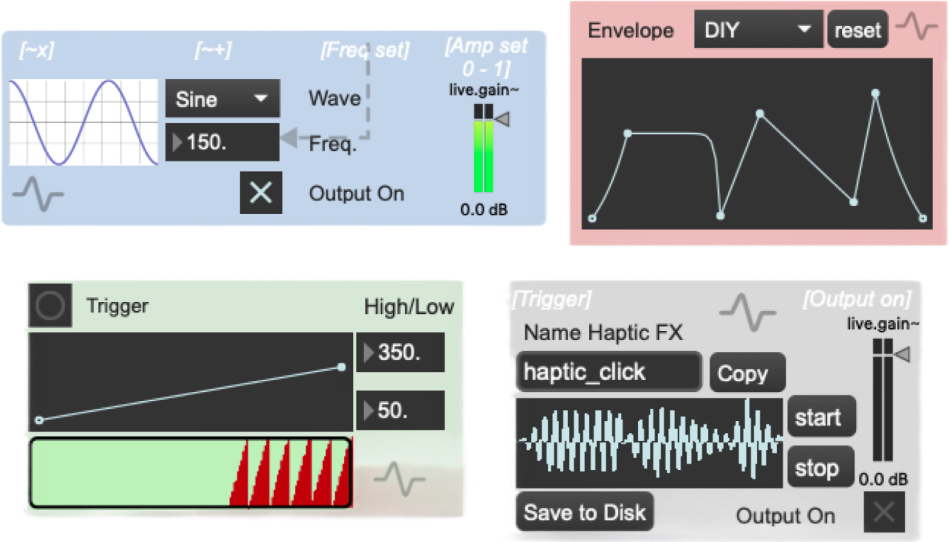


**Fig. 3.2** Sonic Touch Toolkit - design of vibrotactile effect, showcasing the design modules.

Taking inspiration from the haptic rendering framework Syntacts [34], design modules represent the simple building blocks of a vibrotactile effect, which can be chained together to create more complex effects.

- Oscillator (blue): The oscillator module generates waveforms that form the foundation of the haptic signal. Users have the option to select from a sine, triangle, square, rectangle, and white noise. These wave types can be used to create different haptic textures [7].
- Envelope (red): The envelope module includes a number of pre-defined envelopes such as ADSR, ASR, exponential decay, and also the ability to draw a custom envelope. The envelope is multiplied by the incoming signal on the trigger event.

- Automation (green): The automation module offers the ability to create dynamic variations in the haptic feedback. It allows for the programming of changes over a set duration, modulating parameters such as amplitude or frequency.

- Buffer (gray): The buffer allows users to copy the contents of the editing buffer for easy re-use, event triggering, as well as the ability to save the haptic effect to disk.

Whenever a haptic design module parameter is edited, such as changing the frequency or selecting a different envelope type, the editing buffer immediately updates to reflect such changes. Together with the meta-parameters and first three design modules detailed above, the Sonic Touch toolkit covers the often cited four fundamental parameters of haptic effects, which thought to be amplitude, frequency, duration, and envelope [40, 41, 8].

### Mapping modules

The concept of the Sonic Touch toolkit was not to design vibrotactile effects in isolation, but for the rapid prototyping of such effects with DMIs. MIDI and Open Sound Control (OSC) are common DMI communication protocols [38], yet one DMI may send control data very differently to another DMI over the same protocol. If a user wanted to trigger a vibrotactile effect with a specific key press above a certain velocity, they would need to isolate that MIDI note number, and also set a threshold to trigger playback. Thus, the need for custom modules to isolate and compare specific control parameters arose.

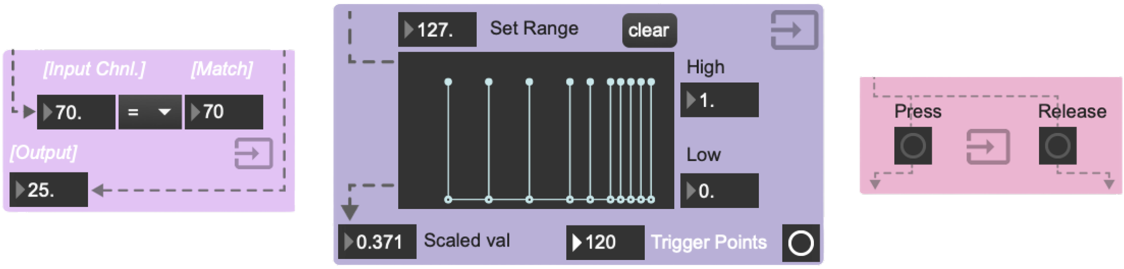


**Fig. 3.3** Sonic Touch Toolkit, mapping modules. From left to right: Filter, Scale, Trigger.

To facilitate the mapping of vibrotactile effects to input controls, three mapping modules are provided:

- Filter (light purple): This module acts a selective filter that only passes a value from inlet to outlet on a matching condition. The module has two inlets: the first for specifying the match criteria (such as a MIDI note number CC channel), and the second inlet for the value to pass through (such as MIDI note velocity or CC value). This allows the user to isolate specific MIDI values.
- Trigger (pink): This module simply outputs a bang through the left outlet if the incoming message is greater than zero, and a bang through the right outlet when zero. This allows haptic effects to be triggered just on key press or key release.
- Scale (dark purple): This module maps the incoming value to a specific range. The scaled value can be outputted through the left outlet (to be mapped for example to the amplitude or frequency of an oscillator module). Alternatively, trigger points can be set along the range of the incoming value, which will output bangs through the right outlet (for the triggering of buffer modules).

## 3.3 Vibrotactile Implementation Case Study: Touché MIDI controller

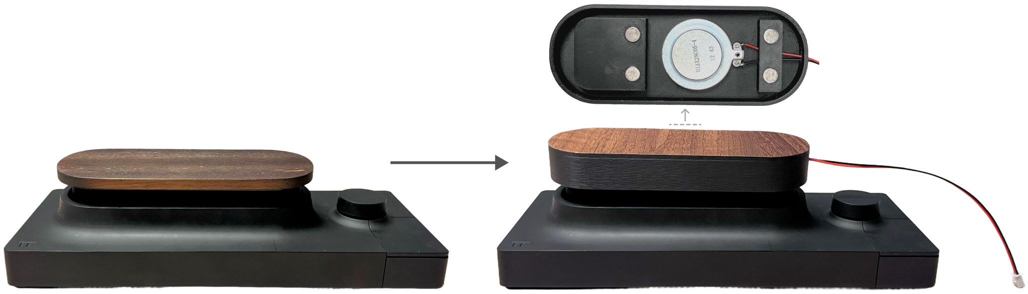


**Fig. 3.4** Touché faceplate redesign with 3D printed part and voice coil embedded.

To demonstrate the Sonic Touch Toolkit's capabilities and explore different feedback strategies, the Touché MIDI controller by Expressive E[1] was augmented with a voice coil actuator. This touch sensitive controller features 4 degrees of continuous positional sensitivity data over MIDI (front press, back press, shift left, shift right), and is typically employed alongside other musical devices to add more expressive gestural control. Given the Touché only provides passive force feedback in the form of a rubber cylinder, it presented an opportunity not only to explore ways vibrotactile feedback could augment the feel and functionality of the controller, but also a learning opportunity on how to approach integrating vibrotactile feedback into further DMIs. We developed two distinct feedback strategies based on Birnbaum's typology: an inherent strategy to make the Touché feel like a standalone 'guiro' instrument, and an augmented strategy to provide control-level information.

A 52mm Tectonic VCA was able to fit underneath the Touché's removable faceplate, however its cramped positioning would cause an unwanted rattling sound. It was decided that 3D printing a new faceplate for the Touché would not only solve this rattle, but would also allow for the larger VCA to be fitted, thus allowing for stronger vibrotactile feedback. With a new faceplate printed, strong magnets were embedded in the faceplate to hold it sturdily to the controller base. An advantage of embedding a voice coil within the device allows not only for vibrotactile feedback, but also auditory feedback if desired.

### 3.3.1 Inherent Feedback Strategy

The concept of transforming the Touché into a standalone instrument through vibrotactile feedback was inspired by a wooden frog guiro, a Latin American percussive instrument played by gliding a stick along the wooden notches to produce a ratchet "croaking" sound.

Through iterative testing, the haptic feel of passing over a ridge was achieved by setting the event length was set to 100ms, with only one repetition. An Oscillator module set to a sine wave at 250Hz was passed into a Envelop module with an exponential decay (Figure 3.5).

The next design decisions are determining how to map this haptic effect to a user gesture on

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[1] https://www.expressivee.com/1-touche

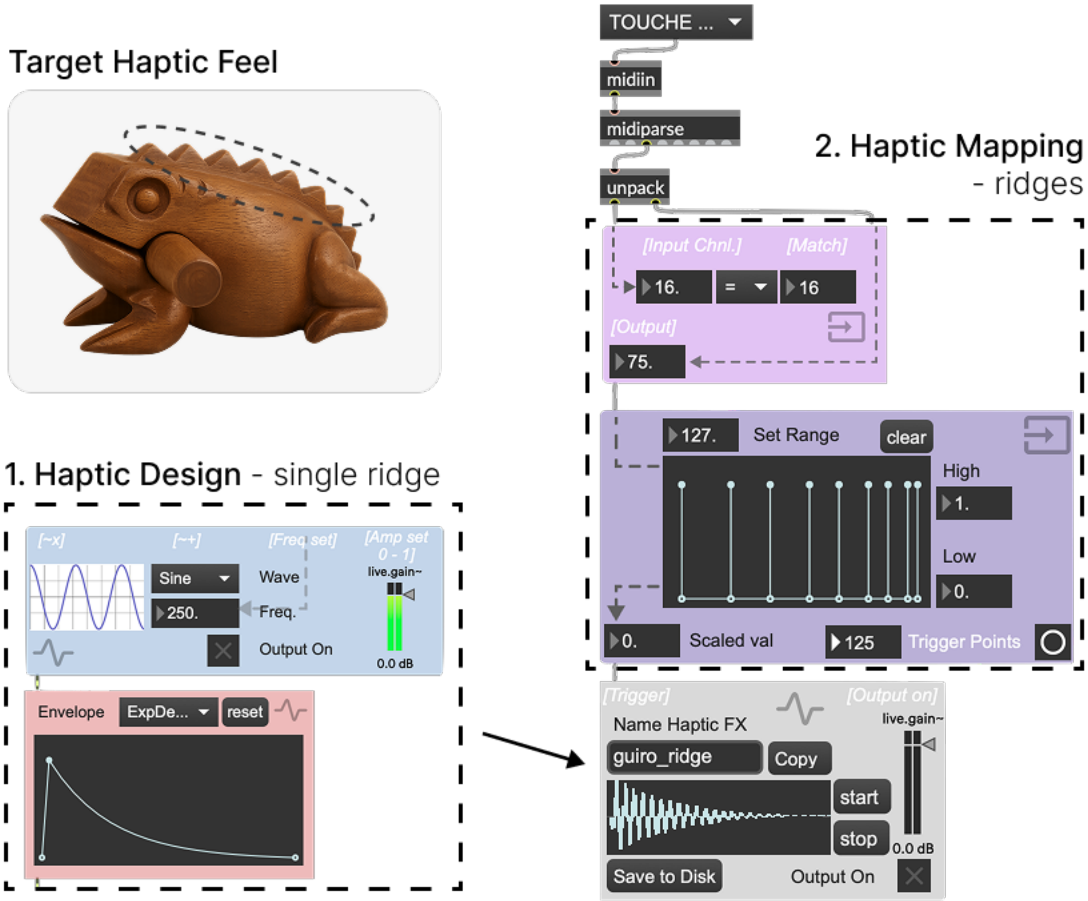

**Fig. 3.5** Implementation of an inherent feedback strategy for the Touché controller, mimicking a guiro. 1. The haptic effect for a single ridge is designed. 2. MIDI data is mapped to trigger the haptic effect at uneven intervals.

the Touché. A common feature of frog guiros are the uneven spacing of the ridge's along the top of the instrument, with a shorter distance towards the back of the frog body and increasing as they near the head. When strum with a stick, this uneven spacing mimics the sound of a frog's croak more closely. To resemble this on the Touché, the front press MIDI data is processed as shown in Figure 3.5. First, the midiparse object separates the MIDI stream, and the Filter module isolates control channel 16. This data is then passed to the Scale module, where trigger points are set at uneven MIDI intervals (20, 40, 60, 75, 90, 100, 110, 115, 120). When a value crosses one of these points, the module sends a 'bang' that triggers the playback of the 'guiro_ridge' effect stored in the buffer module.

### 3.3.2 Augmented Feedback Strategy

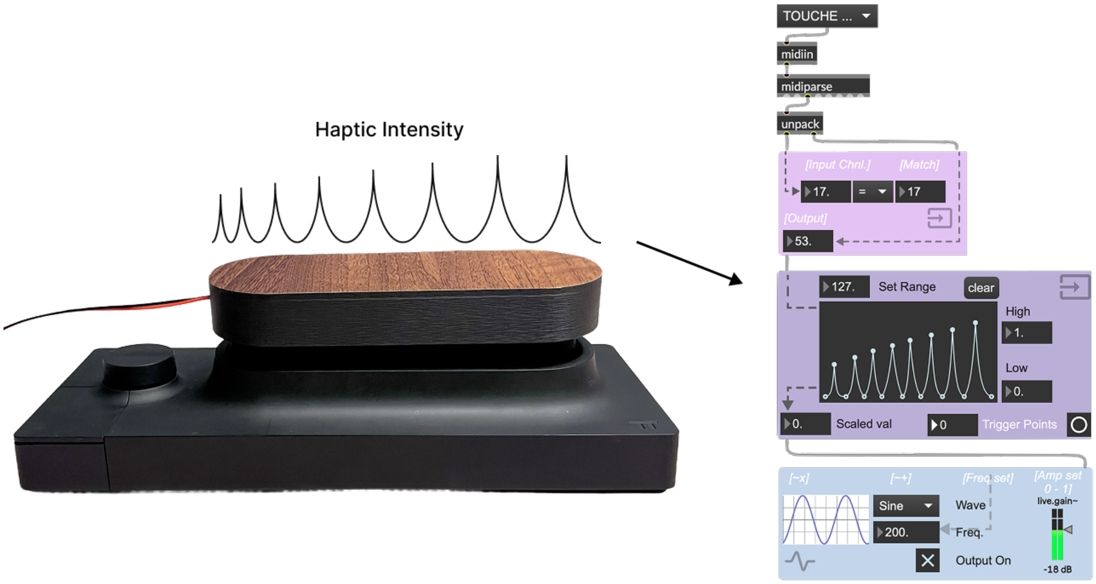

**Fig. 3.6** Implementation of an augmented feedback strategy for the Touché controller. The continuous MIDI output from a press gesture is mapped to modulate the amplitude of a 200Hz sine wave, providing feedback on the user's position.

To demonstrate augmented feedback (i.e. providing additional information not intrinsic to the musical task itself), we based our implementation on work by Rovan & Hayward [7], who proposed that zone-boundary crossing events could be effectively conveyed through variations in noise amplitude and cosine envelope modulation (this concept is illustrated in Figure 3.6). This continuous approach translates readily to the Touché controller implementation. The continuous haptic effect was achieved with a sine wave at 200Hz whose amplitude intensifies when approaching a ridge and reaches maximum intensity at the ridge location. This frequency was chosen as it falls within the range of high human vibrotactile sensitivity [42], making it an effective and clear channel for providing secondary information without being overly intrusive. This augmented feedback on the Touché provides users with spatial information about ridge locations, creating an intuitive understanding of the controller surface's topographical features during interaction. This technique mirrors the approach used in developing a vibrotactile metronome that helped musicians predict upcoming beats [43].

This case study demonstrates the Sonic Touch Toolkit's capacity for creating and mapping both inherent and augmented feedback strategies. By providing a flexible yet unified environment for haptic design, the toolkit serves as the primary research instrument for the exploratory workshops described in the following chapter.

# Chapter 4

# Exploratory Workshops

The Sonic Touch toolkit was developed with the focus of vibrotactile feedback design. As with any tool, it is helpful to have a guide on how to effectively use it. Thus, the main contribution of this thesis comes from studying how DMI designers approach implementing vibrotactile feedback into a diverse set of DMIs and controllers, with the intention to derive device-specific considerations into generalizable strategies for device and haptic feedback design. This chapter presents the workshop design, data collection and analysis methods.

## 4.1 Selection of Workshop DMIs

The 3 DMIs selected were the AKAI MIDI Keyboard, the Linnstrument, and the T-Stick. The reason for selecting these specific DMI's was to represent a spectrum of input device characteristics across multiple dimensions of the musical interface design space [44], and to investigate how these control structures may influence vibrotactile feedback design strategies. Card et al. [45] detail how devices can be understood as a composition of primitive transducers sensing basic physical properties along specific dimensions (e.g., sensing absolute position 'P' along linear 'X', or sensing relative rotation 'dR' around axis 'rZ'). These primitive transducers can be combined in three ways: merge, layout, and connect. Applying the morphology to the 3 DMIs, the AKAI keyboard is largely based on the layout composition, structured around a collection of discrete,

**Fig. 4.1** Workshop DMis

primarily single-dimension inputs (keys, 1-D rotation knobs, and pressure sensing pads). It's control structure provides a baseline for studying vibrotactile feedback strategies in the context of relatively simple control mappings. The Linnstrument was chosen because its primary interaction surface represents a different structural paradigm, with each pad embodies a merge composition to create a multi-dimensional sensing point (x,y, z/pressure). The T-Stick was included to represent a third category of gestural controllers. Structurally, it's a layout composition of various sensors (IMU, FSR, trill), however it differs from the AKAI keyboard in that it connects these multi-dimensional sensors through connect composition (computationally fusing data from these distinct sensors) to interpret holistic physical gestures.

Beyond the differences in their fundamental structural composition, these devices also differ significantly in their capacity for multi-dimensional control. To capture this, we considered the framework proposed by Jacob et al. [46], for understanding the potential interaction complexities arising from the multi-dimensional capabilities of the Linnstrument and T-Stick. This study analyzed the interaction between the control structure on an input device and the perceptual structure of a task, in which Jacob et al. classified input devices as *separable* when they treat multiple dimension inputs as distinct components, and *integral* devices that treat multiple dimensions as a fused whole.

| Feature | AKAI MPK Mini | Linnstrument | T-Stick |
|---|---|---|---|
| **Cost** | Low ($100-$150) | High ($1,500-$2,000) | Not commercially available |
| **Availability** | Widely available | Available from Roger Linn Design | Limited (custom-built research tool) |
| **User-Base Size** | Large (Thousands) | Medium (Hundreds) | Small (Dozens) |
| **Sensors** | Velocity-sensitive keys, pads, rotary encoders | Pressure, X/Y position, Z force sensors (MPE support) | Pressure, tilt, rotation, touch-position sensors |
| **Gestural Range** | Low (MIDI velocity, limited modulation) | High (polyphonic touch, continuous expression) | Very High (spatial gestural interaction) |
| **MIDI/OSC Support** | MIDI (USB) | MIDI, MPE | OSC |
| **Learning Curve** | Easy (traditional keyboard layout) | Medium (grid-based, requires practice) | High (non-traditional, gestural-based) |
| **Customization** | Limited to software mapping | Medium level customization via software | Highly customizable (depends on implementation) |

**Table 4.1** Comparison of AKAI MPK Mini, Linnstrument, and T-Stick

By selecting these three instruments, we aimed to cover a spectrum defined by both structural dimensionality [45] and potential interaction dynamics [46], thereby allowing for a comparative exploration of how different input structure and interaction paradigms influence the design of vibrotactile feedback strategies.

## 4.2 Augmenting the 3 DMIs

As neither of the three DMIs featured active haptic feedback capacity, augmentation was required to enable vibrotactile feedback. In order to fulfill the requirement of keeping the actuator the same size between the three DMIs, the size of the acutator was an important consideration. Generally, the larger the actuator, the stronger the vibrotactile feedback, however internal space limitations were the deciding factor on the size of the actuators (specifically the thickness as it had to fit

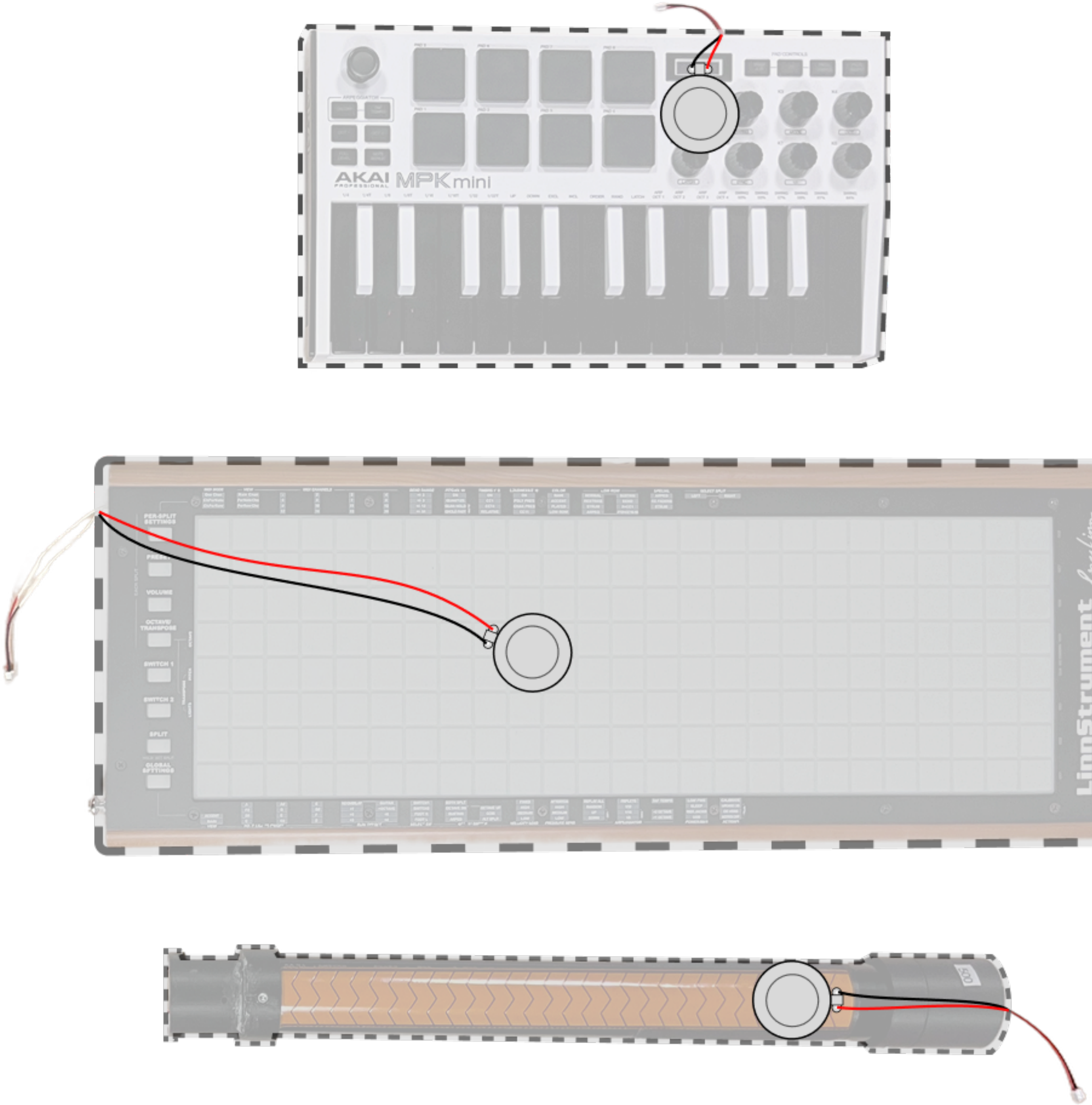

**Fig. 4.2** Voice coil placement on DMIs used in the workshops.

inside the closed body of the DMI). A number of Tectonic voice coil actuators (VCA), ranging from 32mm diameter (9mm thickness) to 52mm (14.5mm thickness), were tested due to their wide bandwidth, ensuring it would not constrain the vibrotactile feedback designs, and relatively low cost (∼\$20 *USD*). A 52mm Tectonic TEAX25C05-4 VCA was selected, as it was able to fit all three DMIs. A small hole was drilled on the back of the AKAI keyboard and cap of the T-Stick to thread the wires. The wires on the Linnstrument were simply threaded through one of the guitar strap button hole (Figure. 4.2).

## 4.3 Methodology

The design workshops were based on a similar methodology by West [4] who took an exploratory approach to investigate how skilled music technology users devised mappings between a audio synthesis and a given DMI.

### 4.3.1 Setup & Tools

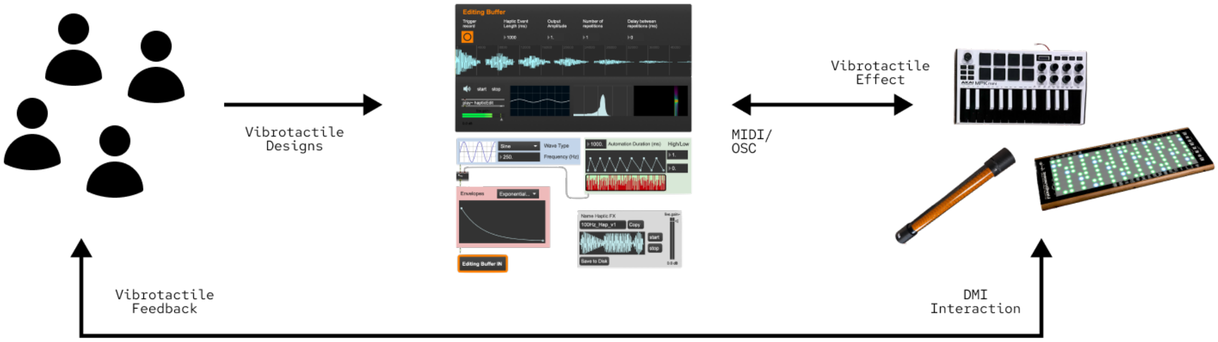

**Fig. 4.3** Workshop design overview. Participants interact with the sonic touch

The workshops were conducted in the Input Devices and Music Interaction Laboratory (IDMIL). Participants were seated at a desk with their given haptically augmented DMI and a laptop running the Sonic Touch Toolkit patch in Max/MSP. The DMIs were connected to an amplifier to power the embedded actuator, and the amplifier connected to the laptop through the 3.5mm headphone jack. The three haptically augmented DMIs, AKAI MIDI Controller, Linnstrument, and the T-Stick were used for the exploratory workshops. Participants were invited to either bring their own synth engine and mappings to the workshop to replicate their own playing setups, or use the Vital VST [1] within the Sonic Touch toolkit for audio synthesis.

The required wired audio connection between the DMI and the external amplifier posed a limitation for the augmented T-Stick users who were used to performing larger unrestrained gestures with a wireless T-Stick. However this was considered a minor issue as the focus of the workshop was on the iterative design of haptic feedback and not on the vibrotactile feedback in a performance setting.

### 4.3.2 Participants

Nine participants took part in the workshops. Participants were purposely matched to a haptically augmented DMI based on their experience with the unaugmented DMI, or experience with a similar DMI. Participants matched with the Linnstrument and T-Stick all had a high level of experience with that given DMI. As for the AKAI MIDI Controller, participants had a high level of experience with similar commercial MIDI controllers.

The purpose of matching participants with DMIs they are already familiar with was to avoid the time spent learning basic instrument functionality, allowing participants to spend the majority of the workshop on vibrotactile designs. Furthermore, this matching hopes to reveal insights into how musicians could use vibrotactile feedback within their own performance contexts.

All of the participants had diverse backgrounds in music and music technology. All were musicians with at least four years experience playing one or more instruments, and all but one participant (P8) specified that they had either Advanced or Expert level of DMI experience. Furthermore, all but one participant (P2) had experience designing and/or modifying one or more DMIs.

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[1] The Vital VST is a spectral warping wavetable synthesizer. The Vital VST accepts MIDI inputs, and thus was used by participants paired with the AKAI MIDI Controller and Linnstrument.

## 4.4 Workshop Overview

My role in the workshops was a *facilitator*. Although participants had experience with their matched DMI, few had experience with designing vibrotactile effects, or perhaps Max/MSP itself, and none with the Sonic Touch toolkit. Given the challenge for participants to envision the full range of possibilities for vibrotactile design without prior exposure or consideration of such feedback mechanisms, I was there to demonstrate the functionality of the Sonic Touch toolkit, present examples of vibrotactile designs and mappings, and most importantly, to assist participants in achieving their vibrotactile design ideas. This facilitation involved guiding participants through technical obstacles without imposing my own design preferences, offering options and asking clarifying questions rather than directing outcomes. When participants described control challenges they faced with their DMI, I would suggest options or ask clarifying questions (e.g., "We could try designing a vibrotactile effect to address that challenge", or "What effect are you trying to achieve?") rather than prescribing solutions (e.g., "I think this should be..."). This approach aimed to maintain the integrity of participants' creative processes while acknowledging the technical guidance needed to overcome the learning curve associated with the toolkit. This distinction is crucial for transparently interpreting the workshop outcomes and properly contextualizing my role as a facilitator in helping participants realize their design goals.

It is important to note that this facilitation role, whilst necessary for the study, has the potential to influence participant decisions. Through providing examples or helping them navigate the toolkit's technical features, I may have guided them towards certain design strategies, or helped them bypass certain technical hurdles that might have otherwise led to different outcomes.

### 4.4.1 Pre-Workshop Questionnaire

At the beginning of the workshop, participants were asked to fill out a questionnaire (see Appendix A). This questionnaire sought to gather information on their musical background, experience with DMI development, and familiarity with haptic feedback and design. The questionnaire also includes a question of tactile feedback importance in DMI design (5-point Likert Scale), which is also asked again post-workshop.

### 4.4.2 Design Session

The design stage lasted 60 minutes, with the participant free to stop the design session early if they felt they had achieved their goals. The laptop screen, toolkit audio, and conversation audio were recorded to track the participant's design processes. The design part of the workshop started by affirming that there was no "right or wrong" way to approach the vibrotactile designs and mappings.

An overview of the Sonic Touch toolkit patch as given, detailing the functionality of the editing buffer and the haptic design modules. A simple haptic effect was designed using the modules and the participant was able to feel the haptic effect on the DMI. I demonstrated changing the editing buffer's haptic event length, repetitions, and delay between repetitions parameters, playing back each haptic effect after each change.

We then took a pause from the toolkit to discuss how the participant used the un-augmented version of the DMI in their own musical practice. Based on their own use-case, and new familiarity with the Sonic Touch toolkit functionality, the participant were asked whether they had any ideas of integrating vibrotactile feedback. From here, the participant took the lead with the Sonic Touch toolkit to start prototyping their vibrotactile designs and mappings. As the participant was not expected to have mastered the use of the toolkit after a short tutorial, whenever the participant described difficulty achieving their vision, we would discuss whether it was a skill issue or a shortcoming of the toolkit, and I offer to help if need be. The design stage concluded either when the time ran out, or the participant notified me that they were satisfied with their vibrotactile designs and mappings.

**Table 4.2** Guiding Discussion Questions

| |
|---|
| Can you walk me through your process for designing the vibrotactile feedback for this DMI? |
| What were the main considerations that influenced your design choices? |
| How did you approach mapping the vibrotactile feedback to the DMI's input sensors or sound output? |
| How do you think the form factor and playing style of this particular DMI influenced your vibrotactile feedback design? |
| Were there any features or capabilities you wished the Sonic Touch Toolkit had that would have helped in your design process? |
| Based on your experience today, what do you think are the key considerations for effectively integrating vibrotactile feedback into DMIs in general? |
| Is there anything else you'd like to share about your experience designing vibrotactile feedback for this DMI or using the Sonic Touch Toolkit? |

### 4.4.3 Post-Workshop Interview & Questionnaire

Following the design stage, participants were asked to reflect on their vibrotactile design experience in an open-ended discussion. This was facilitated with guiding interview questions 4.2.

**Table 4.3** Post-Workshop Participant Questionnaire

| Please rate the following statements on a scale of 1 (Strongly Disagree) to 5 (Strongly Agree): | | | | | |
|---|---|---|---|---|---|
| The vibrotactile feedback I designed enhanced the expressiveness of the DMI. | 1 | 2 | 3 | 4 | 5 |
| The vibrotactile feedback enhanced my sense of direct engagement with the DMI. | 1 | 2 | 3 | 4 | 5 |
| The Sonic Touch Toolkit was easy to use for designing vibrotactile feedback. | 1 | 2 | 3 | 4 | 5 |
| I felt satisfied with the vibrotactile feedback design I created for this DMI. | 1 | 2 | 3 | 4 | 5 |
| The vibrotactile feedback design process was enjoyable. | 1 | 2 | 3 | 4 | 5 |
| On a scale of 1-5, how important do you think tactile feedback is in musical instrument design? (1 being not important, 5 being very important) | 1 | 2 | 3 | 4 | 5 |

Participants were then given a post-workshop questionnaire which consisted of 6 Likert Scale questions 4.3. These were asked to quantify the impact of the vibrotactile feedback on the DMI, and to assess the ease of use of the Sonic Touch toolkit in achieving the participant's goals.

### 4.4.4 Analysis Methods

The analysis of the vibrotactile design workshops consisted primarily of qualitative thematic analysis of the design stage process and post-workshop interview. From the design stage, the video recording of participants use of the Sonic Touch toolkit was watched while taking notes of how participants utilized the toolkit's design and mapping modules to achieve their goals. The design stage audio recording was also transcribed and time-stamped. This allowed me to follow along with the video recording and make note of the participants vocalized thought-process.

These transcripts were subjected to a qualitative thematic analysis using the critical incident technique (CIT) [47] to evaluate the decision making of participants and the toolkit usability. The same analysis technique was used by Young et al. [48] in a study comparing DMI usability between vibrotactile and force feedback. Audio and screen recordings of the participants workshops were first transcribed, and a first pass read through was performed to identify critical incidents. Examples of such included moments when a participant expressed strong emotions or encountered a breakthrough or challenge in their feedback designs. A coding scheme was them developed based on emerging themes: *haptic design, user experience, mapping strategy, toolkit usability, state indication, instrument enhancement, musical context, hardware integration, performance context, communication.* A second read through was done to code each incident into one or more of the above categories, and labeling their sentiment (either positive or negative). From the video recordings of the toolkit, still frames were taken of vibrotactile designs and mappings from the end of the participants session. These design and/or mapping were annotated with the selected haptic parameters (i.e. 150Hz, sine wave), the participants design goal for that mapping (supported from their verbal transcripts), and categorized as either an inherent or augmented feedback strategy (again supported by their vocalized goals). This analysis would reveal whether feedback strategies were shared or contrasted between the different DMI control structures.

# Chapter 5

# Results: Vibrotactile Design Approaches

This chapter presents findings from the workshops. Analysis will be divided across three sections. First, Section 5.2 will present an analysis of vibrotactile design strategies by DMI groups. Qualitative analysis of participant transcripts from the design session and post-workshop interview will be analyzed. This will reveal whether users of the same instrument approach vibrotactile design similarly, providing insight into the influence of instrument form on integration strategies. Feedback from participants regarding the effectiveness of the Sonic Touch toolkit at achieving their design goals will also be presented. Design session and post-workshop transcripts., as well as post-workshop questionnaire data will be used to identify strengths and areas of improvement for the toolkit.

| | AKAI MIDI | | | T-Stick | | | Linnstrument | | |
|---|---|---|---|---|---|---|---|---|---|
| Characteristic | P6 | P8 | P5 | P1 | P7 | P9 | P4 | P2 | P3 |
| Haptic Familiarity | High | NS | Slight | Slight | Mod | Mod | High | Mod | High |
| Vibrotactile Exp | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ | ✓ |
| Audio/Haptic Prog | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Prior DMI Study | ✗ | ✗ | ✓ | ✗ | ✗ | ✓ | ✓ | ✗ | ✓ |

Mod = Moderately, Slight = Slightly, NS = Not Specified

**Table 5.1** Participant Characteristics Grouped by DMI Type

The participant to DMI pairings are in shown in Table 5.1, along with pre-workshop questionnaire data to provide context for the following analysis. All but one participant (P2) had experience designing or modifying a DMI, and all had experience with programming audio or haptic feedback.

## 5.1 Questionnaire Analysis

| Statement | AKAI (n=3) | Linnstrument (n=3) | T-Stick (n=3) | Overall (n=9) |
|---|---|---|---|---|
| Enhanced DMI Expressiveness | 5.0 | 3.7 | 4.0 | 4.2 |
| Enhanced Direct Engagement | 5.0 | 5.0 | 4.0 | 4.7 |
| Satisfied with Feedback Design | 4.3 | 4.3 | 5.0 | 4.6 |
| Design Process Enjoyability | 4.7 | 4.3 | 4.7 | 4.6 |
| Sonic Touch Toolkit Ease of Use | 3.3 | 3.7 | 4.7 | 3.9 |

**Table 5.2** Post-Workshop Questionnaire Ratings (Likert Scale: 1 = Strongly Disagree, 5 = Strongly Agree), Averaged by DMI Group

This section presents the quantitative findings from the post-workshop questionnaires. The nine participants rated their experience on a 5-point Likert scale. Participants' subjective ratings of the experience were highly positive. As shown in Table 5.2, the addition of vibrotactile feedback was rated favorably for enhancing both DMI expressiveness (M=4.2) and the sense of direct engagement (M=4.7). Satisfaction with the created designs (M=4.6) and enjoyability of the process (M=4.6) were also rated highly.

Furthermore, the experience of the workshop appears to have a significant positive impact on the participant's perception of vibrotactile feedback. The question of the perceived importance of vibrotactile feedback in digital musical instrument design was asked both before and after the workshops. As illustrated in Figure 5.1, the average rating increased across every DMI group, with the overall average score increasing from 3.1 before the workshop to 4.1 after the workshop.

**Table 5.4** Categories of CIT Categories with Example Quotes and Definitions

| **Category** | **Definition** | **Example Quote** |
|---|---|---|
| Haptic Design | Comments about the physical characteristics of vibrotactile feedback. | "Just having something that's very like has a good, strong onset... I'll probably switch to an ADSR for this" (P6) |
| User Experience | Comments about subjective feelings and perceptions when using haptic feedback. | "That also would remove the problem I mentioned earlier of only feeling when I'm playing..." (P4) |
| Mapping Strategy | Comments about how vibrotactile feedback is connected to instrument parameters. | "Imagine like a constant frequency, but like an amplitude that's modulated by the [pad] pressure, like the velocity..." (P8) |
| Toolkit Usability | Comments specifically about the Sonic Touch Toolkit interface. | "I would probably be consulting some like documentation if you have that, or like a YouTube video or something." (P8) |
| State Indication | Comments about haptic feedback providing information about instrument state. | "What is important is there's like the safe zone when I don't feel anything, and there's this interval where I feel something, and I know I need to be careful." (P7) |
| Instrument Enhancement | Comments about how haptic feedback improves instrument functionality. | "It makes the instrument alive... it's completely different from what I expect from a MIDI controller. And it can really trigger your creativity or your engagement" (P5) |
| Musical Context | Comments connecting haptic feedback to musical parameters or expression. | "Well, there's definitely something satisfying about the instrument itself vibrating in this kind of coupled relationship with the sound." (P4) |
| Hardware Integration | Comments about the physical implementation of haptic feedback. | "You could potentially tune it in the sense that you could have, like, a fader and say, I want more of the sound going in the thing, or less, depending on the situation..." (P2) |
| Performance Context | Comments about practical implementation in real performance settings. | "For a musician that does a lot of live shows that would probably be really interesting, because sometimes you don't really have good monitoring of what you're playing..." (P2) |
| Communication | Comments about haptic feedback for communication between performers. | "A T-Stick player being able to do some kind of combination of moment or whatever that can be communicated silently to another player..." (P1) |

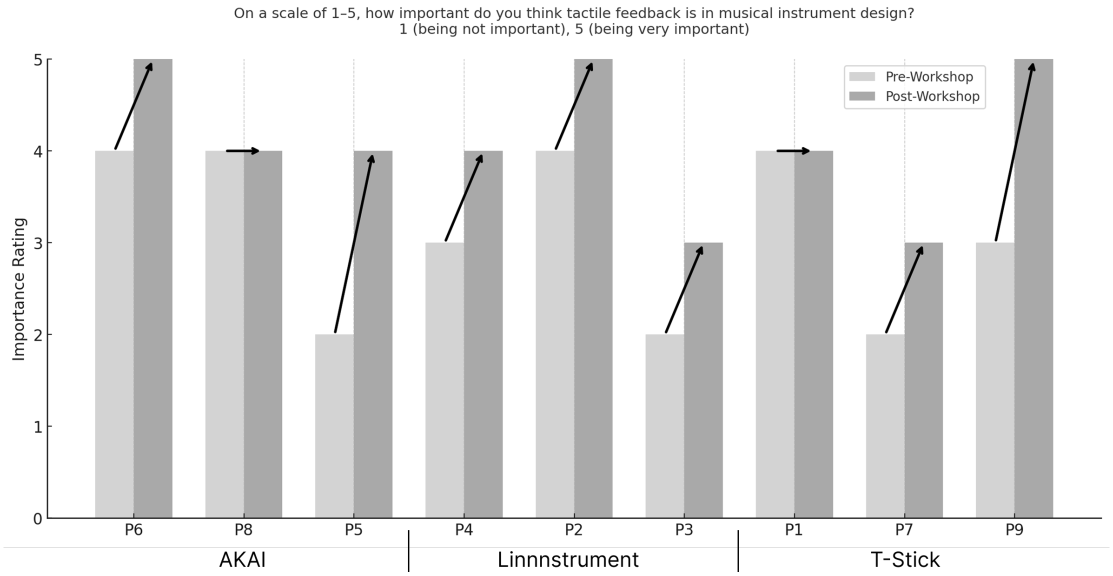


**Fig. 5.1** Perceived importance of tactile feedback in DMI design, rated on a 1-5 scale before and after the workshop.

**Table 5.3** CIT Categories by Sentiment (Sorted by Positive Comments)

| CIT Category | Positive | Negative | Total |
|---|---|---|---|
| Haptic Design | 63 | 6 | 69 |
| Mapping Strategy | 50 | 8 | 58 |
| State Indication | 40 | 1 | 41 |
| User Experience | 38 | 23 | 61 |
| Instrument Enhancement | 31 | 1 | 32 |
| Toolkit Usability | 27 | 22 | 49 |
| Musical Context | 24 | 1 | 25 |
| Performance Context | 16 | 1 | 17 |
| Hardware Integration | 9 | 8 | 17 |
| Communication | 3 | 1 | 4 |
| **Grand Total** | 301 | 72 | 373 |

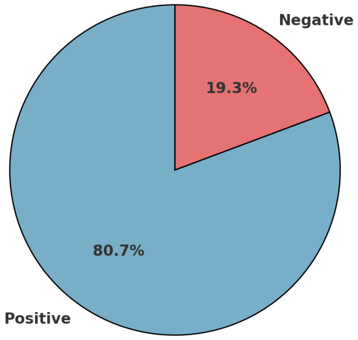


**Fig. 5.2** Sentiment Analysis of Comments

## 5.2 General Sentiment

Across all participant transcripts, a total of 373 critical incidents were identified, with the majority being of positive sentiment (80.7%) suggesting participants valued the addition of vibrotactile feedback. The AKAI keyboard users were most positive about the experience with vibrotactile feedback, with the highest ratio of positive to negative critical incident comments (4.89), compared to the Linnstrument (3.57) and T-Stick (4.32) participants. This positive sentiment is reflected in comments about subjective feelings and perception when using vibrotactile feedback. For example, 8 out of the 9 participants expressed satisfaction with their vibrotactile feedback designs in enhancing the "feel" of playing the DMI:

> *Well, there's definitely something satisfying about the instrument itself vibrating in this kind of coupled relationship with the sound.* (P4)

> *It adds, it's make the instrument alive... is like the like he trigger a new sense... it's completely different from what I expect, of course, from from MIDI controller* (P5)

> *It felt more like I was interacting with an instrument and rather than just a piece of plastic.* (P6)

A couple participants expressed a heightened sense of engagement with the DMI:

> *The fact that I feel my finger vibrating, I think I feel more connected to the instrument... a bit like an acoustic instrument.* (P2)

> *...it's just like, connection to the instrument. Like it feels like I'm the I'm making more of an impact, or like I'm more connected to the impact.* (P8)

Haptic design related comments were most common both overall and by positivity count, which consisted of participants comments on specific parameters of the vibrotactile feedback such as wave-type, frequency, or duration of the haptic design:

> *The low frequency felt a bit more satisfying. So I'll probably see if I go lower what happens... I actually kind of like that. I feel like at 100[Hz] it was it was stronger, more obvious, but here I still feel it enough, and it provides some satisfying feedback without it pulling too much focus.* (P6)

Comments relating to mapping strategies had a very strong positive sentiment basis, making it the second most positively received aspect of the vibrotactile feedback designs. Participants explored a wide range of mapping strategies, between both vibrotactile parameters and DMI controls, audio synthesis parameters to feedback. These mapping varied from continuous and discrete, to linear and logarithmic:

> *If I hit the drum, I get, like, a one shot feedback, sure. Like, if I show if I'm turning a knob, I get some sort of continuous feedback* (P8)
>
> *One other thing I would do is map pressure to amplitude* (P4)

Negative comments were concentrated within two categories: user experience and toolkit usability. Classified as a user experience incident, 5 of the 9 participants commented on the distraction of the hearing the response of the actuator on top of feeling the haptic feedback, with a couple participants (P1, P4) requested headphones to block out the sounds of the vibrotactile actuator.

> *Yeah, the thing it's a bit hard, not to hear the vibration.* (P7)
>
> *Could I have headphones so I can not hear the voice coil as much?* (P4)

These comments were also categorized as a negative incident under hardware integration, as a result of the type and placement of the actuator in the DMIs. There were nearly an equal amount of negative to positive comments overall regarding the toolkit's usability. Negative comments in this category related to users either not being able to achieve their goals with the design and/or mapping modules, or requests for features that the toolkit does not currently posses (such as presets).

> *The sort of rough signal that I was hoping to produce, is not exactly coming to life, not as rough... it's not as noticeably different as I might have liked.* (P4)
>
> *I don't have patience for that. So for me, that's why I guess I like the analog stuff...* (P8)

## 5.3 Feedback Strategy Classification

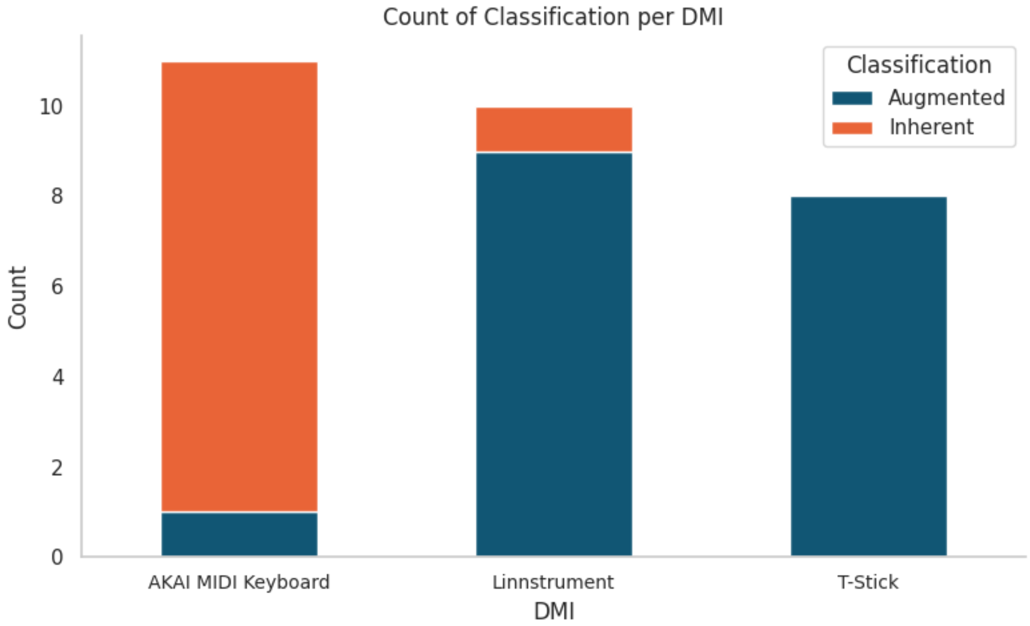


**Fig. 5.3** Distribution of Inherent and Augmented feedback across DMIs, showing how each instrument influences feedback design choices.

In total 28 vibrotactile strategies were identified between the three DMIs; 11 for the AKAI keyboard, 10 for the Linnstrument, and eight strategies for the T-Stick. Designs were classified in the post-workshop analysis as either inherent or augmented based the design goals of the participants during the workshops, and an analysis of the vibrotactile designs themselves. Vibrotactile strategies that were task-intrinsic, such as triggering a haptic pulse with a pad hit, was classified as inherent ("*It's good at connecting the what I'm hearing to what I'm feeling.*" P6). On the other hand, vibrotactile strategies that provided additional information beyond the musical task itself, such as feedback to give an indication of position within a sensor range, was classified as augmented feedback. From a higher level classification of feedback strategies, 5.3 illustrates how strategies differed distinctly between DMIs. Participants with the AKAI keyboard strongly favored inherent feedback, with only one augmented strategy implement. The inverse was true for the Linnstrument, strongly favoring augmented feedback strategies with one inherent design. The

T-Stick was the only DMI to feature only one type of strategy, with all participants implementing augmented feedback.

## 5.4 Feedback Strategies by DMI

While the previous section provided a broad overview of inherent and augmented feedback strategies and their distribution across the DMIs, this section delves deeper into the specific vibrotactile designs implemented for each instrument. We will examine the AKAI MIDI Keyboard, Linnstrument, and T-Stick, analyzing the unique approaches, mapping choices, and participant experiences.

### 5.4.1 AKAI MIDI Keyboard

**Table 5.5** CIT Categories by Sentiment for AKAI DMI (Sorted by Positive Comments)

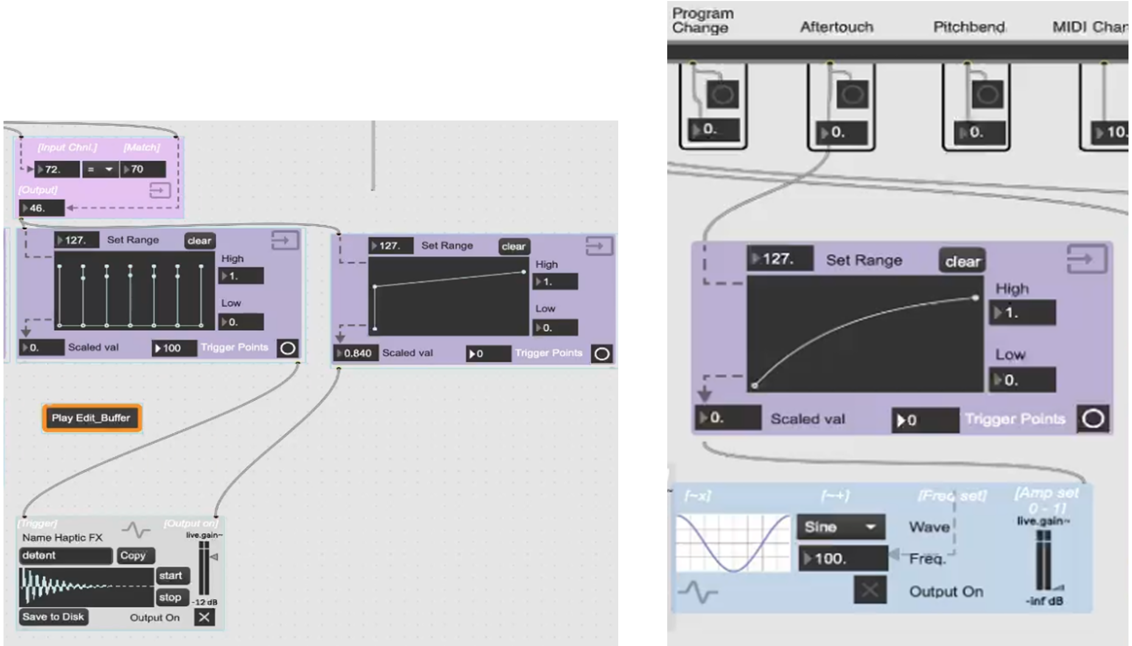
| **CIT Category** | **Positive** | **Negative** | **Total** |
|---|---|---|---|
| Haptic Design | 20 | 0 | 20 |
| Mapping Strategy | 19 | 4 | 23 |
| Musical Context | 14 | 0 | 14 |
| Instrument Enhancement | 12 | 0 | 12 |
| User Experience | 10 | 3 | 13 |
| Toolkit Usability | 9 | 9 | 18 |
| Performance Context | 5 | 0 | 5 |
| State Indication | 4 | 0 | 4 |
| Hardware Integration | 0 | 3 | 3 |
| Communication | 0 | 0 | 0 |
| **Grand Total** | 93 | 19 | 112 |

Participants praised how the vibrotactile feedback made the keyboard more interesting to play (P5, P6), and gave the participants a heightened sense of control.

> *Feels like I'm actually doing something, as opposed to just like triggering digital events* (P8)

Mapping strategy and haptic design were the first and second most discussed categories. Participants experimented with different mappings between rotary knobs, pads and key presses. Two participants (P6, P8) followed a similar workflow, first experimenting with designing and mapping discrete haptic clicks to the rotary knobs:

> *It lets me know the range of the parameter without seeing it, which is really useful on these kind of continuous encoders that can spin in any direction.* (P6, comment also classified under Communication category)



(a) P6: Knob vibrotactile design and mapping.

(b) P8: Pad vibrotactile design and mapping.

**Fig. 5.4** AKAI MIDI Keyboard vibrotactile design examples. (a) P6's design mapping a rotary knob (CC 70) to trigger 'detent' pulses and modulate amplitude. (b) P8's design mapping pad pressure to modulate a continuous sine wave.

P6's vibrotactile design and mapping can be seen in Figure 5.4a, where they utilize the filter object to isolate the MIDI knob control value (70), which routes into two scale objects. The first scale object sets trigger points across a 127 range, the output of which triggers a buffer module containing an enveloped haptic pulse named "detent" which the participant designed earlier. A second scale object is used to modulate the amplitude of the haptic effect based on the position of the knob (increasing in intensity as the user gets closer to the end of the knob's range).

They both then turned attention to the drum pads, mapping the amplitude of a continuous feedback module to the pad pressure:

> *I think that what was appealing about the pad is that I had to press harder to make more [feedback], it's like I had to put more energy in to get more energy out.* (P8)

Once participants started bringing in VST audio, they all expressed a strong desire for the vibrotactile feedback to be inherently tied with the auditory feedback.

> *I would love to have a response, an haptic response from the tool that could be representing the frequency, the frequency spectrum that I was triggering. (P5)*
>
> *For me, the mappings inherently need to be tied to the sound.* (P6)
>
> *When there's that feedback loop, I'm more inspired to spend time crafting the sound to be something that not only sounds nice, but feels nice to play.* (P8)

Out of the three DMIs, AKAI MIDI users reported had the highest level of Musical Context related comments, with 13 positive comments and no negative comments. Examining their haptic designs as well as CIT comments revealed a common trait among this group, in which participants designed vibrotactile feedback that imitated the mappings between the DMI and the VST. Two participants (P6, P8) made a mapping between the pad pressure and continuous vibrotactile intensity feedback to mimic the auditory mapping between the pad and the VST cutoff frequency (Figure 5.4b).

> *like when it's at like a low frequency, having like low vibration frequency, and then as you kind of increase the cutoff frequency of the filter, it vibrating at a higher frequency.* (P8)

In the post design session interview, P5 confirmed this, describing their approach to vibrotactile design as largely informed by what the heard from an audio synthesis perspective. This was reflected in their design session, as they attempted to match the tempo of an arpeggiator to the duration of haptic feedback pulses.

> *my approach, it's basically based on the audio effects, mostly.* (P5)

The majority of negative comments for the AKAI keyboard related to toolkit usability. These ranged from participants requesting something beyond the functionality of the toolkit, such as recalling previous haptic effects in buffers (P5), or being unsure of how a design module worked (P6).

### 5.4.2 Linnstrument

**Table 5.6** CIT Categories by Sentiment for Linnstrument DMI (Sorted by Positive Comments)

| CIT Category | Positive | Negative | Total |
|---|---|---|---|
| Haptic Design | 23 | 2 | 25 |
| Mapping Strategy | 18 | 2 | 20 |
| User Experience | 16 | 10 | 26 |
| State Indication | 12 | 0 | 12 |
| Musical Context | 9 | 1 | 10 |
| Instrument Enhancement | 7 | 1 | 8 |
| Hardware Integration | 6 | 1 | 7 |
| Toolkit Usability | 5 | 9 | 14 |
| Performance Context | 4 | 1 | 5 |
| Communication | 0 | 1 | 1 |
| **Grand Total** | 100 | 28 | 128 |

The top three CIT categories for the Linnstrument participants were haptic design, mapping strategy, and user experience. Positive user experience comments related to the change in perception of the Linnstrument with the addition of vibrotactile feedback:

> *I definitely think it enhanced the expressiveness for sure... I was, like, kind of curious and skeptical before well, like the first time we talked, I didn't really know what to expect. And I'm actually quite surprised of how effective it is.* (P2)

> *Whereas the direct feedback of audio coming from the instrument that I feel like that taps into a very deep psychological thing in the brain* (P4)

All participants commented positively on using vibrotactile feedback to give an indication of sensor values (state indication) for the pad interaction. This could be explained by the more complex gestures the Linnstrument pads enable (compared to the AKAI keyboard), and with the added layer of complexity invited more complex feedback solutions.

> *I think another interesting use case for this is you could actually use that to say you wanted to precisely set a parameter, but only with pressure.* (P2)
>
> *Just anything that would let you play the instrument more easily without looking at it... that kind of helps me know where I am in relation to the other notes on the instrument.* (P3)
>
> *So my first thought is, well, maybe it could be used as some sort of secondary information stream.* (P4)

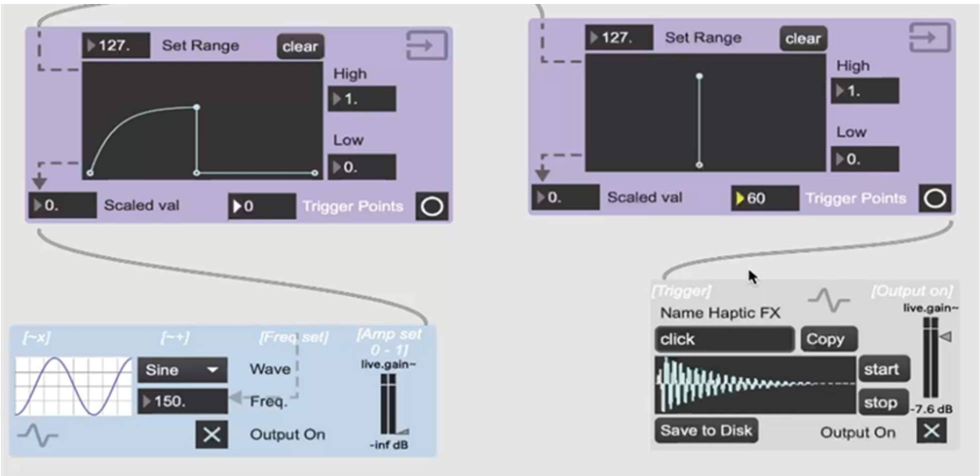


**Fig. 5.5** P3 vibrotactile strategy, utilizing both discrete and continuous feedback to indicate boundary approach and crossing.

Seven out of the eight vibrotactile feedback strategies for the Linnstrument were augmented in nature. All participants experimented with using both discrete and continuous vibrotactile feedback to give indication of the control state of the instrument, sometimes in conjunction as P3 demonstrated (Figure 5.5) by using increasing the amplitude of a continuous oscillator module to approach a defined boundary, and a discrete haptic pulse to indicate passing of that boundary.

P4's vibrotactile implementation strategy was based on an issue they had described achieving a fine level of pitch control during private practice of the Linnstrument:

> *That's something I remember struggling with, was playing in tune with the full like raw, exposed pitch bend data. And that's an application that this kind of toolkit could be very interesting.* (P4)

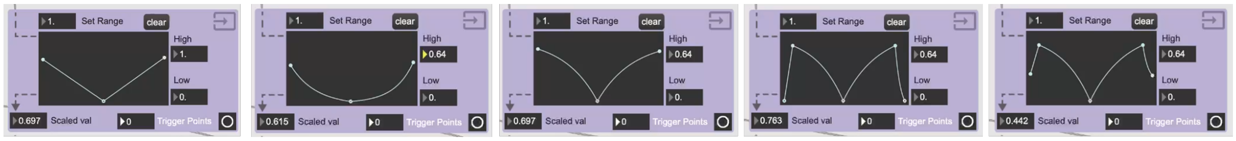


**Fig. 5.6** P4's iterative design of the mapping function for the Linnstrument, showing different envelope shapes to modulate feedback amplitude based on pad press.

P4's design process is illustrated in Figure 5.6, as they iterated through different envelope shapes to map a pad press to the amplitude of a continuous oscillator module. Starting from the left, the v-shape envelope meant that there was no feedback at the frequency center of a note, and would increase in intensity as they participant de-tuned the note by slightly rolling their finger off center. The next two envelopes show P4 experimenting with changing the gradient of the lines. They then add two more points that slightly decreased the intensity of the feedback to indicate the user is at the edge of the note boundary. Whilst P4 designed satisfaction with their augmented vibrotactile designs and mappings, they indicated in the post design session interview that they would instead prefer more direct, inherent feedback:

> *I think I would, I would pick this mapping I've devised over nothing, because it does seem to have a practical utility, but I would much rather have just the audio going through the voice coil.* (P4)

This desire for a one-to-one mapping of auditory to haptic feedback falls inline with comments from participants from the AKAI MIDI keyboard group who preferred inherent feedback strategies.

> *Well, there's definitely something satisfying about the instrument itself vibrating in this kind of coupled relationship with the sound.* (P4)

The majority of negative comments were localized to the two categories of user experience and toolkit usability. P3 expressed that they wouldn't have picked up on the ability to playback the haptic editing buffer using an external trigger without explicit guidance from myself, and also commented on the challenge of starting the process with a blank design slate:

> *We started with building this buffer without necessarily like mapping it to to like expressive parameters coming out of the instrument... I think made it a little harder to picture how it would manifest itself.* (P3)

### 5.4.3 T-Stick

**Table 5.7** CIT Categories by Sentiment for T-Stick DMI (Sorted by Positive Comments)

| CIT Category | Positive | Negative | Total |
|---|---:|---:|---:|
| State Indication | 24 | 1 | 25 |
| Haptic Design | 20 | 4 | 24 |
| Toolkit Usability | 13 | 4 | 17 |
| Mapping Strategy | 13 | 2 | 15 |
| User Experience | 12 | 10 | 22 |
| Instrument Enhancement | 12 | 0 | 12 |
| Performance Context | 7 | 0 | 7 |
| Hardware Integration | 3 | 4 | 7 |
| Communication | 3 | 0 | 3 |
| Musical Context | 1 | 0 | 1 |
| **Grand Total** | 108 | 25 | 133 |

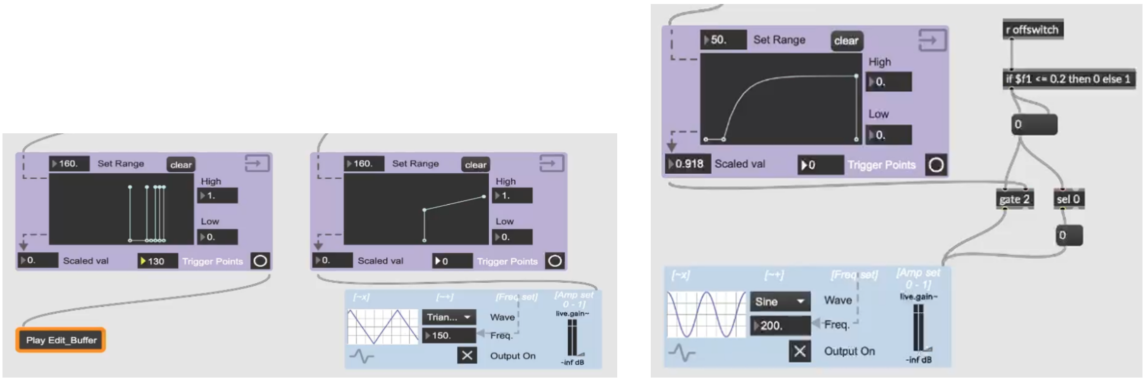
As users of the T-Stick generally design their own custom synthesis patches, participants in the workshop were encouraged to connect their own synthesis patch to inspire ideas for the haptic feedback in their own musical contexts. Results from the sentiment analysis revealed that T-Stick users were very positive overall to the addition of vibrotactile feedback. Participants described feeling a stronger connection to the instrument, with two participants ascribing this to a heightened level of control the vibrotactile feedback was enabling:

> *It's now a two, two way controller, which just conceptually is, is so cool. ...the idea that the computer can also talk to us, guide us, let us know something the two way, the back and forth, yeah, conceptually, kind of change the change the thing for sure.* (P1)

> *I think, like the informative part would help me with the expressiveness, because even if I don't really like this word, but expressiveness is, in fact, a lot about control, but very fine control... It's like you, you know where you are, what you're doing, and you're able to do like, some subtle variations, some more subtle things.* (P7)

P9 described how vibrotactile feedback increased the embodiment of the T-Stick:

> *It definitely it makes me feel like the T-Stick kind of fits better in my mental model of what the T-Stick is when I when I think about it... and like having that vibration, it's not so much just like waving a tube around.* (P9)



(a) P7: FSR pressure mapped to discrete pulses and continuous ramped feedback as approach threshold.

(b) P1: Gyroscope mapped to increase in vibrotactile feedback as user moves away from vertical orientation.

**Fig. 5.7** Vibrotactile feedback strategies to communicate T-Stick sensor state.

Participants responded most positively to the applications of vibrotactile feedback for state indication, reflected in all seven vibrotactile strategies for the T-Stick being augmented in nature. Two distinct strategies manifested, the first consisted of conveying control level information regarding the state of the T-Stick. When asked about possible vibrotactile feedback strategies, P7 detailed the difficulty of knowing the state of continuous sensors such as the FSR or gyroscope through feel alone. P1 likewise suggested applying vibrotactile feedback to provide control-level detail of the T-Stick sensors.

> *[Feedback] could be applied to the FSR, because it's very hard to have a feeling of the actual values. It's very hard to say if you are at 80 or 90% it's very hard to feel it so to have like yes, the feedback to okay, you are getting close to this threshold.* (P7)

> *I would be really interested next to do something with continuous value, maybe in terms of almost pedagogy kind of thing, like, let's say I want to practice having it super vertical... imagine you have a class of young T-Stick players, and they need to all be kind of in this range.* (P1)

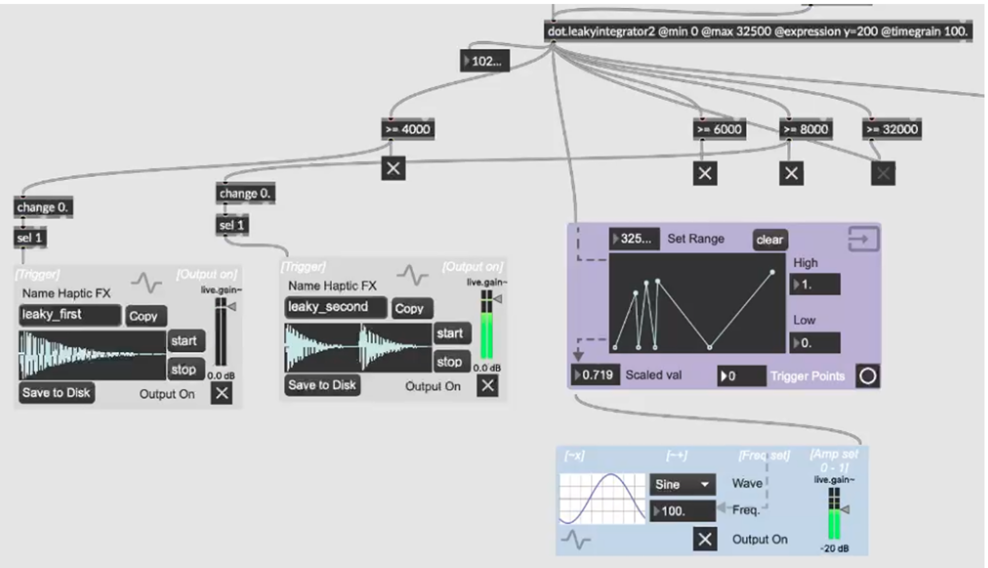


**Fig. 5.8** P9: Vibrotactile feedback to give user information regarding patch state.

Due to the mapping complexity within some of the participant's patches, the second strategy was to provide information regarding the state of the synthesis patch itself. For example, P9 brought to the workshop a T-Stick synthesis patch which measured the length of time the pressure was applied to the FSR, and at determined time intervals, would trigger different musical events. Illustrated in Figure 5.8, P9 experimented with two distinct vibrotactile strategies to provide feedback on the length of time the FSR was pressed, the first strategy consisting of two discrete pulses labeled "leaky_first" to indicate the first time-interval, and a double pulse labeled "leaky_second" to indicate the second time-interval. The second strategy involved using the scale object, which scaled the range of the leakyintegrate2 between 0 and 1. The participant then drew an envelope with 4 peaks, each larger than the previous which scaled the amplitude of a sine wave set to 100Hz, providing continuous feedback to user as they held down the FSR. In the post-workshop interview section, P9 described another complex T-Stick patch they had developed, and theorized how how vibrotactile feedback could be helpful to monitor the state of this multi-channel, agent-based patch.

> *I do think that having a haptic effect to that would be good to like know what presets I'm using, because, in theory, I should be able to identify them by ear, but we're smashing 24 objects in an eight channel panner down to stereo... when I do have to do something in stereo or in mono, all those kind of haptic effects would help me better, kind of distinguish all that from the general like muck.* (P9)

One T-Stick user was very interested in the idea of using vibrotactile feedback to communicate between performers.

> *I'm really interested in kind of silent communication with with our patches and stuff, and even with other collaborators. And so, you know, a T-Stick player being able to do some kind of combination of moment or whatever that can be communicated silently to another player, meaning like, "oh, let me start something", or, "oh, follow me." Or "begin the next section". You know, this is really something that interests me.* (P1)

Negative reactions to the vibrotactile feedback centered around user experience. Two participants complained about hearing the voice coil along with the feedback, with one participant asking for ear covers to mitigate this (they did not receive ear-covers). This was a consequence of having the audio output and the vibratile output come from two different sources. Perhaps integrating the audio output directly into the T-Stick would reduce the distraction from audible vibrotactile feedback. P7 also described their wariness of over-using vibrotactile feedback on the T-Stick, with passive haptic feedback, such as varying material textures, being sufficient in some cases:

> *I feel the difference in the texture, sure, okay, and to me, that's enough. It doesn't need to be a vibration. I see it could be that, like the thing like this, what we tested is cool, but at some point, maybe it can take some practice, but I don't want to have to focus on the vibration, on everything.* (P7)

# Chapter 6

# Discussion

The workshops were successful in exploring how musicians approached vibrotactile feedback design across a diverse set of DMIs, shedding light on our primary research question: "How do musicians/instrument designers conceptualize and implement vibrotactile feedback across various digital musical instruments?". The general response to the addition of vibrotactile feedback across all three DMIs was largely positive, from enhancing the "feel" of playing the instrument to enabling a finer level of control through a secondary stream of information. Using Birnbaum's [9] topology to frame the functional goals of the feedback, we observed the different approaches to vibrotactile feedback between DMI groups; AKAI users predominantly designed inherent feedback strategies, while Linnstrument users and T-Stick users strongly favored augmented feedback strategies.

To understand why users favored inherent or augmented feedback for their given DMI, this chapter will analyze the influence of DMI characteristics using Card et al.'s [45] framework to understand structural composition, and Jacob et al.'s [46] framework to understand multi-dimensional interaction.

## 6.1 The Experiential Value of Vibrotactile Feedback

One of the most encouraging results from the workshops was the overall positive reaction towards the vibrotactile feedback. Two prominent themes emerged from participants' experiences across the three digital musical instruments: *enhanced connection and engagement* and *increased expressivity and control.* Participants frequently equated the vibrotactile feedback to the feel of playing acoustic instruments. For instance, P6 on the AKAI remarked the experience felt "*more like I was interacting with an instrument and rather than just a piece of plastic*", and P2 on the Linnstrument described that "*the fact that I feel my finger vibrating, I think I feel more connected to the instrument... it's like an acoustic instrument*". This subjective sense of connection is reflected in the post-workshop questionnaires, where participants gave an average rating of 4.7 out of 5 for 'Enhanced Direct Engagement with the DMI'.

To explain this, we can turn to O'Modhrain & Gillespie's [1] work on performer-instrument interaction. The authors challenge the traditional view that more "precise" control over an instrument improves musicians' ability to express themselves, contending open air interfaces and touchscreens as "failures" of musical interfaces as they only provide "information exchange". Instead they argues that 'dynamic coupling' between acoustic instruments and the instrumentalist through the haptic channel allows what Cadoz [3] defines as an "energy exchange" back and forth between player and instrument, and thus supports the development of higher levels of musical expressiveness and skill development[1]. Whilst acoustics instruments naturally have this coupled relationship from mechanical excitation to acoustic output, digital instruments suffer from a haptic disconnect as there is no inherent physical system to create energy exchange. Given these constraints, whilst vibrotactile feedback may be classified by O'Modhrain & Gillespie's as still being "information exchange" rather than their idealized model of mechanical energy exchange through a physical system, it may be the best available alternative for restoring bidirectional interaction. Participant's who designed *inherent* feedback strategies artificially re-established this dynamic coupling that Cadoz advocated for, which resulted in strong experiential response, notable in increasing the potential expressiveness of the DMIs:

> *It's good at connecting the what I'm hearing to what I'm feeling.* (P6, AKAI)

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[1] The authors cite experimental evidence showing that simulated haptic interfaces that model the touch response of instruments resulted in more accurate performances of playing tasks [49, 50, 51]

> *It just feels so much more expressive. It feels like I'm actually doing something just like. It feels like there's more connection. Obviously, auditory feedback definitely helps like more than nothing, but actually the haptic feedback is really good.* (P8, AKAI)

> *I definitely think it enhanced the expressiveness for sure...I'm actually surprised by how effective it is.* (P2, Linnstrument)

Not only can vibrotactile feedback mimic the timing and intensity of natural mechanical feedback, it can go a step further than an acoustically coupled systems to provide explicit state information. This is presented in the participants *augmented* feedback strategies. Of the 28 vibrotactile strategies, 17 of them (1 AKAI, 9 Linnstrument, 8 T-Stick) provided the participant with control level information. 11 of these augmented feedback designs were made to provide the participant tactile positional information within a continuous range (the rotary encoder on the AKAI keyboard, pads on the Linnstrument, FSR & IMU on the T-Stick). One T-Stick participant used augmented feedback to give tactile confirmation that a jab gesture had been registered, describing it particularly useful in the case when a gesture triggers a subtle auditory event which can be easily missed. At an even higher level of complexity, vibrotactile feedback was used to communicate system-wide information, as one T-Stick participant demonstrated by using vibrotactile intensity to provide tactile feedback about a clock timer within their synthesis patch, demonstrating how augmented feedback can convey not just sensor states but also broader 'patch-level' control information.

Our findings align with O'Modhrain & Gillespie's position on the value of *inherent* feedback in achieving enhanced playability and expressiveness (either mechanical energy exchange, or as detailed above mimicked through digital vibrotactile feedback). Participants who designed inherent feedback often aimed to mimick a coupled dynamic system between the player's body and the instrument, resulting in a stronger experiential connection to their instrument. However, our results challenge the view that augmented feedback, which functions as "information exchange," is a lesser substitute. The T-Stick, physically furthest from any traditional acoustic instrument, demonstrated that augmented feedback can foster a significant meaningful connection between player and instrument. Participants using the T-Stick reported that this informational feedback was crucial for achieving a higher degree of control, which they directly linked to expressiveness:

> *I think, like the informative part would help me with the expressiveness... expressiveness is, in fact, a lot about control, but very fine control. So I think it helps, in the end, having a finer control... It's like you, you know where you are, what you're doing, and you're able to do some subtle variations, some more subtle things.* (P7, T-Stick)
>
> *It does improve the feeling of playing, I will at least say, and I feel like I'm more aware of what's happening other than just like the usual* (P9, T-Stick)

These participant responses highlight the advantages vibrotactile feedback can provide over purely mechanical system, in both mimicking natural mechanical feedback (*inherent feedback*) and providing control and system state information (*augmented feedback*).

## 6.2 Influence of DMI Characteristics on Feedback Design

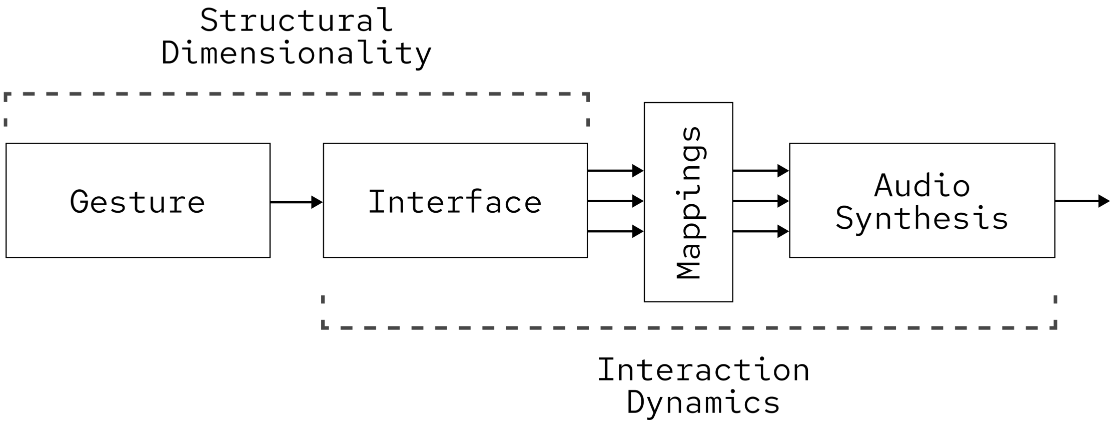


**Fig. 6.1** A model of DMI interaction illustrating the relationship between Gesture, Interface, Mappings, and Audio Synthesis, contextualized by Structural Dimensionality and Interaction Dynamics.

In the previous section, we analyzed how participants responded to their inherent or augmented feedback strategies. In this section, we aim to understand why participants on the AKAI keyboard leaned towards inherent feedback strategies, whereas Linnstrument and T-Stick participants favored augmented feedback strategies. Card et al.'s framework will help explain the devices are, structurally, and Jacob et al.'s framework helps explain how users interact with the multi-dimensional capabilities those structures provide. We will detailed how a DMI's structure enables certain interactions, and how those interactions (and their perceived complexity) drive the feedback requirements.

### 6.2.1 Structural Dimensionality

As described in Chapter 4, Card et al.'s [45] morphological analysis proposes that instead of seeing input devices as a random collection of inventions, we can view them as "points in a parametrically described design space." This space is comprehensive, containing all existing and potential input device designs. Devices in this space can be understood as a composition of primitive transducers sensing basic physical properties along specific dimensions, which can be combined into more complex input devices in three ways, *merge*, *layout*, and *connect* composition. These compositions define the 'structure' of an input device. Here we will analyze the three DMIs through Card's morphological lens, and assert that structure of a DMI significantly shapes the nature of user interaction, which in turn influences the type of vibrotactile feedback (inherent or augmented) users deem most appropriate.

The AKAI keyboard is primarily characterized by *layout* composition; a collection of independent transducers (keys, knobs, and pads) are placed together on the same device. The keys are laid out in keyboard formation, the knobs in a row, and the pads in a grid. Within each group, each element maintains individual input-output mappings but share physical proximity to each other. This structure lends itself to more separable control tasks, where the user adjusts one parameter independently via a dedicated physical control, such as triggering a note with a key and bending the pitch of that note with a knob.

In contrast to the AKAI's predominantly discrete controls, the Linnstrument combines multiple sensing transducers into a single point of control to form a *merge* composition structure. Each pad on the Linnstrument merges x-position, y-position, z-pressure, and release velocity sensing into a single interaction point, with a single finger movement on a pad yielding a tuple of multi-dimensional data. The individual pads are then arranged in a grid using *layout* composition.

The T-Stick features a number of individual sensors (FSR, IMU, capacitive touch strip) which are physically distributed across the body of instrument in *layout* composition. Whilst these sensors can be interacted with interdependently, the T-Stick is fundamentally designed around the principle of computational interpretation and transformation of sensor data to form a *connect* composition structure. Card et al. define connect composition "when the output domain of one device is mapped onto the input domain of another device." While some mappings might be direct (e.g., raw FSR pressure to volume), most gestures on the T-Stick, such as 'jab', 'brush', 'rub', are achieved by mapping the output domain of the physical sensor (the raw data streams from the IMU or the capacitive strip) onto the input domain of the gesture recognition algorithm [4]. The combination of *layout* and *connect* composition results in an instrument where the control signals are often not tied to one specific sensor's direct output, but are emergent from the user complex gestural interact to control the sound.

An important nuance to make here is that we are applying these structural definitions depending on the 'typical' use of the given DMI. Just as the T-Stick is primarily a connect composition through mapping sensor values to higher level gestures recognition, the same *could* be done on the AKAI keyboard. For example, one could create a mapping layer that detects when the user performs some complex gesture, such as holding down a key at the same time as pressing a pad and rotating a knob to trigger some. Whilst this is *possible*, it is not usually how users of the AKAI MIDI keyboard would use the device.

### 6.2.2 Interaction Dynamics

We can now look at how user's perceived and interacted with the control dimensions offered by each DMI's structure. Jacob et al. [46] categorized input devices based on how they navigated a 'control space'. Imagining this control space with an 'initial' set of parameters and a 'goal' set, Jacob et al. classified input devices by the way in which their controls allowed for movement through this perceptual space. Movement between the initial and goal parameter through independent controls is defined a *separable* movement, or city-block pattern. If the control device allows straight line movement between parameters, movement is in the Euclidean space, cutting through dimensions of control, and is defined as *integral* control. This framework aligns with Hunt and Kirk's [52] distinction between analytical and holistic modes of interaction in musical performance. They argue that separable control structures encourage analytical thinking, where users focus on parameters sequentially. In contrast, integral control structures support holistic thinking, allowing users to perceive the overall effect and manipulate interconnected information streams simultaneously.

As established, the AKAI features a layout composition of control (keys, pads, knobs). This leads to predominantly *separable* interaction dynamics, where users address individual parameters through distinct controls. The control of one parameter (e.g., filter cutoff via a knob) is generally independent of controlling another (e.g., note pitch via a key). These separable and clear interaction dynamics reduce the need for informational feedback to disambiguate control states or mappings, and therefore the feedback becomes about enhancing the physical feel, engagement, and directness of these already understandable actions, aligning with Birnbaum's concept of inherent feedback and reflected in the 10 of 11 inherent feedback strategies on the AKAI keyboard. For example, P6 (AKAI) expressed a desire for close coupling, stating, "*For me, the mappings inherently need to be tied to the sound*" while P5 (AKAI) focused on the experiential enhancement, noting, "*it adds, it's make the instrument alive... is like the like he trigger a new sense... it's completely different from what I expect, of course, from from MIDI controller. And it can really trigger your kind of, your creativity or your way your engagement*". P8 (AKAI) further captured this sentiment by remarking that "*It feels like I'm actually doing something... It feels like there's more connection. Obviously, auditory feedback definitely helps. Like, sure, more than nothing. But the actually, the haptic feedback is really good.*"

In contrast, the Linnstrument's merge composition per pad (fusing x, y, and z sensing) creates localized, multi-dimensional control points. This merged input structure naturally leads to integral interaction dynamics. A single finger movement simultaneously varies X, Y, and Z parameters, which are often perceived and manipulated as a unified gestural input, where control 'cuts across all the dimensions'. This integral nature significantly increases interaction complexity. Disentangling the specific contribution of X, Y, or Z to the sound, or precisely controlling one while holding others stable, can be challenging, and the high importance participants placed on "state indication" is a direct response to these challenges. This complexity and the integral nature of the control structure drives the strong preference for augmented feedback, with users require explicit informational cues to navigate this rich but potentially confusing multi-dimensional space effectively. P3 (Linnstrument) highlighted this need for navigational aid, stating that feedback which "*helps me know where I am in relation to the other notes on the instrument*" would allow them to "*play the instrument more easily without looking at it.*" P4 (Linnstrument) explicitly considered feedback as an informational channel: "*So my first thought is, well, maybe it could be used as some sort of secondary information stream*". Furthermore, P2 (Linnstrument), when considering pressure control, suggested feedback could help "*precisely set a parameter, but only with pressure*" indicating a desire for augmented cues to help isolate or monitor a specific dimension within the integral control. An important subtly to note: each of the 200 integral pads on the Linnstrument act as individual keys which are independent of one another, making the Linnstrument a mix between low level integral parameter control, and at a high level separable note selection control. This hybrid structure helps explain P4's stated preference for more direct, inherent feedback in the post-workshop interview, treating the Linnstrument less as a complex multi-dimensional controller and more like a traditional keyboard.

T-Stick's layout composition of diverse sensors is combined with connect composition (sensor fusion) to produce holistic, multi-dimensional control gestures. The sensor fusion often results in emergent control dimensions that are effectively integral in nature. For example, a holistic gesture such as 'jab' (derived from IMU data) involves the interpretation of multiple sensor inputs into a unified control signal. Furthermore, participants generally described creating complex mappings between T-Stick gestures and synthesis parameters (such as controlling the grain size in a granular synthesizer or multi-agent based synthesis approach). This complexity and the often integral or abstract nature of control explain the unanimous preference for augmented feedback among all three T-Stick participants. Participants required augmented vibrotactile feedback to understand the trigger point of fused gestures (i.e. 'jab') and to gain insight into how physical actions map to sound, especially with non-obvious or configurable mappings. Even when feedback relates to a single sensor's parameter such as the FSR sensor, in the context of the T-Stick's overall programmability and potential for complex fusion, this feedback serves an informational role about a software-defined state or threshold rather than enhancing a "natural" physical feel (e.g., indicate vertical orientation, FSR pressure, or FSR press time). P7 (T-Stick) directly linked the informative part of feedback to enhanced expressiveness and control: "*It's like you, you know where you are, what you're doing...*" P1 (T-Stick) envisioned augmented feedback for "*pedagogy kind of thing, like, let's say I want to practice having it super vertical*", highlighting its role in state indication for learning. P9 (T-Stick) saw its utility in a complex performance context: "*...haptic effect to that would be good to like know what presets I'm using... help me better, kind of distinguish all that from the general like muck.*" The difficulty in perceiving raw sensor states was articulated by P7 (T-Stick) regarding FSR values: "*...it's very hard to have a feeling of the actual values... feedback to okay, you are getting close to this threshold*", underscoring the need for explicit, augmented cues for abstract thresholds.

The signal type itself, whether the vibrotactile effect was designed as a discrete event (a distinct pulse, click, or short burst) or a continuous sensation (an ongoing, modulated vibration), also appeared to influence the design. For inherent feedback (6 discrete, 5 continuous), discrete signals often served to emphasize a physical action and its direct sonic consequence, such as the arpeggiator triggered by P5's key presses or the drum sounds initiated by P6's pad strikes. Continuous signals in inherent feedback, like P6 on the AKAI using continuous feedback to match the pressure of a pad, suggests a deliberate design intent to create a temporally aligned auditory-tactile experience. For augmented feedback (8 discrete, 10 continuous), discrete signals were well-suited for explicit informational cues like event notifications. T-Stick participants used discrete feedback to indicate correct jab gesture (P1) and state indications of FSR pressure (P7). In contrast to discrete pulses to provide state information (such as warnings), continuous signals were also used to provide dynamic, fine-grained state information, such as P2 on the Linnstrument using it to indicate y-value on a pad, or P1 to indicate correct vertial orientation on the T-Stick.

In conclusion, the interaction dynamics, separable for the AKAI and largely integral for the Linnstrument and T-Stick, can be understood and explained through Card et al.'s [45] structural framework and Jacob et al.'s [46] interaction paradigm. Separable interactions where the control dimensions are distinct and mappings are often transparent align with inherent feedback's role in enhancing the direct playing experience. Conversely, complex and integral interactions necessitate augmented feedback's information support for clarity and state-awareness associated with navigating a richer, high-dimensional control space.

## 6.3 Vibrotactile Parameterization and Mapping Choices

This section transitions the discussion from the underlying reasons for choosing inherent versus augmented feedback to the specific design choices participants made in realizing their vibrotactile feedback. The analysis will cover the selection and rationale behind various vibrotactile parameters, such as waveform, frequency, duration, amplitude, and envelope, as well as the strategies employed to map these parameters to DMI input controls or sound synthesis parameters. This exploration of detailed parameterization and mapping choices will reveal how these decisions are deeply intertwined with the intended function of the feedback, whether to enhance the intrinsic feel of an interaction or to provide explicit state information, thereby clearly distinguishing the practical implementation of inherent versus augmented feedback strategies.

### 6.3.1 Vibrotactile Parameters

Looking closer at the features of vibrotactile designs themselves, we find that participants explored a wide range of vibrotactile parameters across waveform, frequency, duration, repetition, and enve-

| Parameter | Inherent (11) | Augmented (18) |
|---|---|---|
| **Waveform** | Sine (8), Triangle (3) | Sine (17), Triangle (1) |
| **Frequency** | 80–100Hz | 100–300Hz |
| **Duration** | 50–100ms | 50–250ms |
| **Repetition** | 1–4 reps | 1–3 reps |
| **Delay** | 0–150ms | 0ms |
| **Envelope** | Exp decay (3), ADSR (2), ASR (1) | Exp decay (8) |
| **Signal Type** | Discrete (6), Continuous (5) | Continuous (10), Discrete (8) |

**Table 6.1** Vibrotactile Design Parameters by Classification

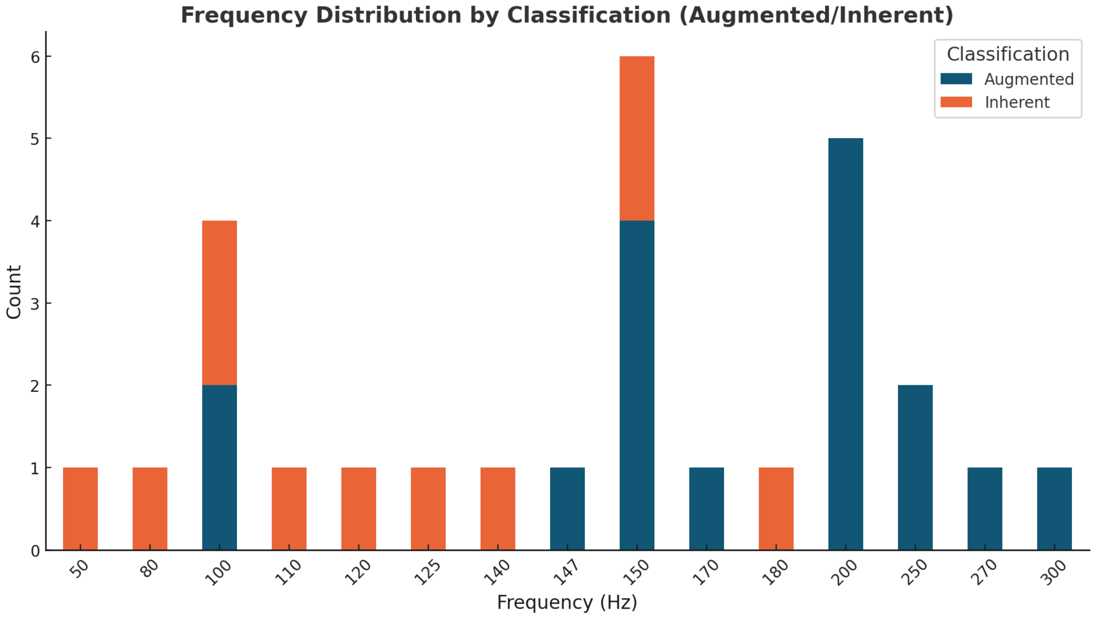


**Fig. 6.2** Distribution of frequencies (Hz) used in vibrotactile designs, categorized by feedback classification (Inherent vs. Augmented).

lope type (Table 6.1). Looking at the frequency distribution of vibrotactile designs reveals distinct grouping between inherent and augmented feedback classifications. Inherent feedback strategies utilized frequencies as low as 50Hz up to 180Hz, which the medium frequency of 120Hz. Augmented feedback strategies featured a higher frequency range between 100Hz and 300Hz, with a medium frequency of 200Hz. Lower frequencies in inherent feedback may have been chosen to mimic the tactile sensations associated with the lower-frequency components of acoustic instruments. This approach tends to support Birnbaum's (2007) notion of inherent feedback conforming to pre-existing cognitive models of acoustic vibrotactile experiences, where the feedback is perceived as an intrinsic part of the instrument rather than a separate informational layer. This was supported by P6 on the AKAI, who stated that "*the low frequency felt a bit more satisfying. So I'll probably see if I go lower what happens a I actually kind of like that. I feel like at 100 [Hz] it was it was stronger, more obvious, but here I still feel it enough*". Conversely, higher frequencies generally utilized for augmented feedback may have been selected to create more distinct, salient alerts that stand out clearly, as the skin's vibrotactile sensitivity has been shown to peak around 250Hz [42].

Regarding waveform, sine waves were predominant in both classifications (25 out of 29 designs), likely chosen for their ability to create smooth, 'natural' sensations in inherent feedback or clear tonal alerts in augmented feedback. Only three vibrotactile designs featured a triangle wave type. Whilst it has been shown that vibrotactile discrimination is indeed possible between simple (sine) and complex (square, triangle) wave types [53], the limited use of more complex wave types by participants could be explained as they were significantly more audible than the sine wave without offering a sufficiently distinct haptic experience to justify the increased audibility. P6, using the AKAI, highlighted how audibility influenced tactile perception when switching from a sine to a triangle wave: "*They do feel different. Not that much different through the plastic, and I think it's, I'm partly thinking it's different, because I can hear the difference, and that's kind of influencing my perception of it.* (P6, AKAI changing from sine to triangle)". Furthermore, P3 on the Linnstrument indicated that sine waves could be more haptically noticeable than square waves, despite having less harmonic content and lower audibility: *I'm just surprised that something, I would assume, that [square wave] with more harmonic content would feel would haptically be more notable noticeable. I kind of don't, I don't feel that. Like I can even see that this is, like, actually quieter than the square wave, but it's more it feels more noticeable.*

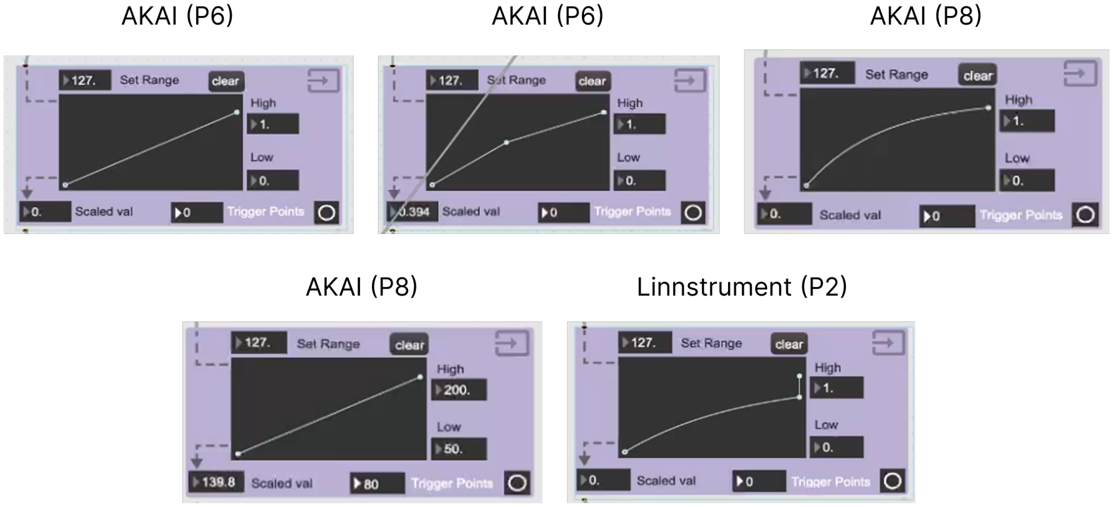
For duration and repetition, inherent feedback often employed shorter durations, sometimes with carefully timed repetitions, potentially to create "click-like" or "impact" sensations that reinforce direct actions. Augmented feedback designs showed more varied durations, possibly to encode different forms of alerts or state information, with a general lack of delay between repetitions suggesting a desire for sharp, immediate information. In terms of envelope, inherent feedback utilized a wider variety, such as ADSR and ASR, to shape the "physicality" or "expressiveness" of the feedback, perhaps to match sound envelopes or gesture dynamics. P6 (AKAI), for instance, considered an ADSR envelope: "*I think, yeah, just having something that's very like has a good, strong onset. So I think I'll probably switch to an ADSR for this*". The strong preference for exponential decay in augmented feedback likely aimed to create clear, concise, and unambiguous alerts or pulses that convey information efficiently without lingering.

In summary, participant's vibrotactile parameter choices appear to distinctly differ between inherent and augmented feedback. Inherent designs often utilized parameters conducive to integration, naturalness, and embodied feel, while augmented designs prioritized parameters that would ensure the clarity, distinctness, and unambiguous perception of information.

### 6.3.2 Mapping Strategies

Beyond the intrinsic parameters of the vibrotactile effects, the intent behind how these effects were mapped is crucial for understanding their function. In this context, "mapping" refers to the process of linking of a designed vibrotactile effect (whether inherent or augmented) to specific DMI input parameters, gestures, or characteristics of the audio output.

Many inherent feedback mappings, particularly on the AKAI, were relatively simple and one-to-one (e.g., pad pressure directly to vibration amplitude). Mapping to DMI inputs consistently

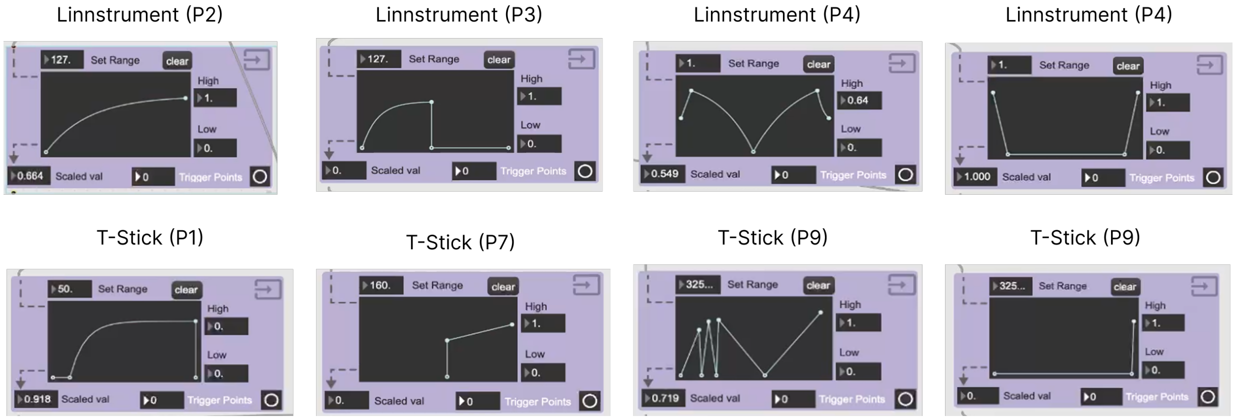

AKAI (P6) AKAI (P6) AKAI (P8)

AKAI (P8) Linnstrument (P2)

**Fig. 6.3** Inherent mapping transfer functions for continuous vibrotactile feedback.

centered on creating a direct, congruent tactile sensation that reinforced the feel of the physical input gesture itself, thereby enhancing embodiment and the sense of direct manipulation. This was often achieved through simple and smoothly continuous mapping functions, as seen in the mapping graphs for AKAI users such as P6's and P8's continuous pad and knob mappings in Figure 6.3. These linear or gently curved mappings translated physical actions like pressing or turning into proportionally changing vibrotactile feedback, enhancing embodiment. P8's (AKAI) note that "*I think the what was appealing about the pad is that I had to press harder to make more... it's like I had to put more energy in to get more [vibrotactile] energy out*" underscores this intent for a direct, straightforward mapping function.

In contrast, augmented feedback mappings often featured more complex transfer functions to convey nuanced information or respond to specific recognized states. A significant number of augmented mappings featured more complex logic, including discontinuities, distinct zones, or sharp nonlinearities in their transfer functions as seen in Figure 6.4. This was evident in T-Stick strategies where the purpose was to indicate correct jab gesture (P1), or provide discrete indication of FSR pressure (P7). This complexity is most notable in P9's (T-Stick) continuous mapping for the FSR length of time held down, demonstrating a sawtooth-like pattern with sharp


Linnstrument (P2) Linnstrument (P3) Linnstrument (P4) Linnstrument (P4)

T-Stick (P1) T-Stick (P7) T-Stick (P9) T-Stick (P9)

**Fig. 6.4** Augmented mapping transfer functions for continuous vibrotactile feedback.

peaks and valleys, clearly defining multiple discrete states or stages within a continuous input. These more complex mapping functions in augmented feedback were designed to translate sensor data into specific, informational cues crucial for control, navigation, learning, or confirming system interpretation within the DMI's interaction space.

## 6.4 Evaluation of the Sonic Touch Toolkit

The Sonic Touch Toolkit was developed to facilitate the rapid prototyping and mapping of vibrotactile effects, and was the primary tool used in the workshops. The guiding design principles were simplicity, versatility, and immediacy. The goal in this evaluation is to access the toolkit's effectiveness based on feedback from participants, identifying strengths and areas of improvement so that future DMI designers have an effective tool to implement vibrotactile feedback in their own projects. Overall, sentiment towards the toolkit was mixed but generally positive (27 positive CIT comments to 22 negative, Table 5.3). Suggestions of features to improve the toolkit were regarded as positive sentiments, whereas comments that simply noted a flaws or difficulty were counted as negatives. This mixed-but-positive sentiment is mirrored in the questionnaire responses, where participants gave the toolkit an average 'Ease of Use' rating of 4.0 out of 5, with T-Stick users rating it highest (M=4.7) and AKAI users rating it lowest (M=3.3).

### 6.4.1 Strengths and Positive Feedback

From a technical perspective, the toolkit appeared largely successful at achieving the goal of versatility when looking at the wide range of haptic designs and mappings participants created within the short duration of the workshops. This is reflected in 29 haptic designs in Table 6.1, and the unique mapping functions across all DMI's featured in Figure 6.3 and Figure 6.4.

We can also look experientially at participant's responses to the toolkit. Regarding interface design and modularity, participants found the toolkit generally intuitive and responsive for basic operations. P8 (AKAI) found the toolkit "*pretty intuitive*", and "*it's responsive, which is nice that you can just like click*", referring to the editing buffer automatically updating when selecting preset values, supporting the toolkit's goal of simplicity and immediacy. After explaining the haptic design modules, P1 (T-Stick) stated "*I think you did an amazing job in terms of UX... I'm really convinced by the proposition*", and then later claimed "*it's really cool to think about these as two separate things that we stack easily with a buffer*" when describing simultaneously triggering two discrete haptic effects. Encouragingly, even though the majority of participants did not have prior experience with haptic design, the toolkit's modular design seemed to simplify the design process enough to achieve the participant's goals, reflected in P3's (Linnstrument) claim that "*it's still extremely usable and useful*" and confidence that "*even without [the facilitator] here, I would have been able to reason my way through making that [haptic feedback] shape*". Furthermore, as many of the participant's had experience with Max/MSP, some appreciated it's integration within a patch, with P6 (AKAI) excited about the idea of integrating a "*simplified... abstracted view*" of the toolkit into a Max for Live patch, and P7 (T-Stick) hoping that "if this is easily integrated in a [T-Stick synthesis] patch while, while you devise your mapping... I can envision it like this".

### 6.4.2 Challenges and Areas for Improvement

As the participants benefited from the workshop facilitator being present to guide them through the toolkit's functionality, some participants felt a need for clearer documentation or tutorials, especially for more complex features. When asked whether they felt confident achieving vibrotactile designs on their own, P8 (AKAI) stated "*I would probably be consulting some like documentation if you have that, or like a YouTube video or something like that*", and P7 (T-Stick) similarly felt "*a user manual or documentation to understand a bit how it works*" would benefit them. The addition of better documentation and more haptic design and mapping examples would hopefully resolve some of the ambiguity that participant's felt towards the function of certain modules, as P6 (AKAI) noted that "*it's not entirely obvious*" whether the right inlet of the buffer module controlled the gain of the haptic effect.

A notable challenge from the facilitator's point of view was the "blank slate" approach, in which participants found it difficult to visualize haptic feedback effects without prior experience with haptic feedback design, or being comfortable with the capabilities of the toolkit. This may have been a limitation of the workshop setup, in which the haptic design modules were introduced first before the mapping modules, perhaps making it difficult for participant's to mentally connect the feedback to a performance gesture. This limitation is supported by P3's (Linnstrument) comment: "*we started with building this buffer without necessarily like mapping it... I think made it a little harder to picture how it would manifest itself*". The 'blank slate' problem, combined with the lack of documentation, may have led participants to create simpler, more foundational haptic designs than they might have with a library of presets.

Whilst the mapping modules provided flexibility in haptic design, it also introduced complexity. For this reason, a preset feature was requested from a number of participants. P7 felt that whilst there was "a lot of flexibility... its good for experimentation" but "If you want to re-implement, once you are satisfied with something, you don't necessarily need to have everything", wishing to "have something more compact... just one abstraction with all the presets you are happy with". Likewise, P6 (AKAI) felt that a preset feature similar to that found on digital synthesizers such as "*five or ten pre-made effects that either you make or the user can make and customize that very quickly*" would simplify the design process and save time.

> *So my first instinct would be to just play the audio through the voice coil, okay, which I recognize would not make extensive use of the framework that you've built. But that's*

> *basically the immediate first thought that I would have is just, well, what does the sound feel like?* (P4, Linnstrument)

The above participant's comment explicitly addresses a fundamental challenge of the toolkit's influence on the outcome of the workshops. While the Sonic Touch Toolkit was designed to provide versatility and facilitate complex haptic design, its structure may have inadvertently created a bias towards complexity. P4's instinct was for the most direct form of inherent feedback, a simple audio pass-through, yet they felt a pressure to engage with the more extensive "framework that you've built". This suggests that the toolkit, by presenting an array of design and mapping modules as the primary way to achieve vibrotactile feedback, may have unintentionally steered participants toward designing novel vibrotactile signals from scratch, rather than first exploring the tactile feel of the existing audio synthesis. This challenge may be compounded by the "blank slate" problem discussed above, where starting the design process without clear examples or straightforward audio pass-through option directed users into a certain workflow. Therefore, a key area for improvement is to make simple, direct audio-tactile feedback an explicit and easily accessible feature within the toolkit, validating it as a design choice equal to more complex signal synthesis.

Despite these challenges and areas for improvement, the overall effectiveness of the toolkit in demonstrating the value of vibrotactile feedback is promising. After a single 60-minute session using the toolkit, participants' average rating of the importance of tactile feedback in DMI's rose from 3.1 to 4.1 out of 5. This suggests that providing designers and musicians with an accessible tool for haptic exploration can fundamentally elevate their appreciation and understanding of its role in digital music interaction.

# Chapter 7

# Conclusion

This thesis was driven by a central research question: How do musicians and instrument designers conceptualize and implement vibrotactile feedback across various digital musical instruments, and to what extent does an instrument's fundamental structure influence these design choices? To answer this, a series of exploratory workshops were conducted where participants used the newly developed Sonic Touch Toolkit to design feedback for three structurally diverse DMIs. The findings show that the integration of vibrotactile feedback is not arbitrary, but a strategic choice directly informed by the interaction paradigm of the DMI in question.

The development of the Sonic Touch Toolkit serves as a successful proof-of-concept for a flexible, accessible platform for haptic prototyping. It's effectiveness was not only proved by the variety of strategies participants were able to implement in a short time, but also its impact of raising the participant's average rating of the importance of tactile feedback in DMI after a single session. This highlights that equipping musicians and designers with tools for haptic exploration, they develop a greater appreciation and understanding of its role in digital music interaction.

The primary contribution of this work is the identification of a clear and generalizable design pattern. The workshops revealed that for DMIs with discrete controls and separable interaction dynamics, like the AKAI MIDI keyboard, designers gravitate towards inherent feedback. Their focus was on enhancing the physical feel of direct actions and reinforcing the link between gesture and sound to create a greater sense of embodiment. In contrast, for DMIs with multi-dimensional or fused-sensor controls that invite integral interaction, such as the Linnstrument and T-Stick, designers strongly favored augmented feedback. This choice was a response to the instruments' complexity, with feedback being used to provide crucial informational cues for navigation, precision, and awareness of the system's internal state.

These findings offer applications for the design, teaching, and performance of digital musical instruments. For the commercial design of DMIs, these findings suggest that the "one-size-fits-all" approach is not sufficient. Manufacturers could add experiential value by implementing feedback that aligns with the instrument's interaction model, enhancing the feeling of playing and connection on keyboard style controllers with separable controls, while providing more feedback style cues on more integrally controlled gestural instruments. For music pedagogy, augmented haptic feedback could help inexperienced musicians understand the gesture-to-sound mappings, or sensor-value ranges and bounds, enabling them to practice precise control of a digital instrument. Finally, for musical practice, this work highlights the potential to use haptic feedback as an additional communication channel with other musicians during performance, and providing real-time awareness of complex synthesis parameters that might otherwise be imperceptible during live performance.

This research opens up several promising directions for future investigation. A important next step would be to investigate how musicians utilize vibrotactile feedback within their own musical performer when given longer with the toolkit to explore and familiarize themselves with. This could include further longitudinal workshops with a wider variety of DMIs would help confirm and refine the identified design patterns. The Sonic Touch toolkit will also be further developed based on participant's feedback, with more robust documentation and features such as presets to address the "blank slate" issue, and a more obvious audio pass-through option to mitigate any bias towards complexity. Future investigation on optimal actuator type and placement would also be beneficial to address the audible noise from the voice-coil which was a distraction for some participants. Furthermore, the small number of participants of three per DMI necessarily limits the generalizability of these findings, and therefore future work should aim to validate these design strategies with broader studies involving more participants. Whilst this study was designed to capture the experiential value of haptic feedback, future studies could explore the impact of the haptic strategies on objective performance metrics such as musician's pitch and timing accuracy, or error rates with and without the augmented feedback.

Ultimately, this research suggests that a digital instrument's interaction paradigm fundamentally shapes which vibrotactile feedback strategies will resonate with users. By providing both practical tools and theoretical frameworks, this work enable more intentional and strategic integration of haptic feedback in digital musical instruments.

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# Appendix A

## A.1 Sonic Touch Toolkit - User Guide

The following is a brief user guide for the Sonic Touch Toolkit, detailing the core components used by participants in the workshops.

### A.1.1 The Editing Buffer

The "Editing Buffer" is the central workspace for prototyping a vibrotactile effect. It receives its audio signal from the **Editing Buffer IN** inlet, which is fed by the Haptic Design Modules. It displays the resulting waveform visually and allows for the adjustment of several meta-parameters:

- **Haptic Event Length (ms):** Sets the total duration of the haptic event.
- **Number of Repetitions:** Defines how many times the event will repeat.
- **Delay Between Repetitions (ms):** Sets the time between repetitions.

The buffer updates in real-time as parameters in the design modules are changed, providing immediate tactile and visual feedback.

### A.1.2 Haptic Design Modules

These modules are the building blocks for creating the haptic signal itself. They are connected using standard Max/MSP patch cords to form a signal processing chain. The final signal from this chain is patched into the **Editing Buffer IN** inlet to be prototyped. A example chain might be **Oscillator** → **Envelope** → **Editing Buffer IN**.

- **Oscillator (Blue):** The sound source for the haptic signal. Generates waveforms including Sine, Triangle, Square, Rectangle, and White Noise. Modules can be chained together (e.g., two oscillators) to create more complex waveforms.
- **Envelope (Red):** Shapes the amplitude of the incoming signal over time. Includes presets (ADSR, ASR, Exponential Decay) and a "DIY" mode for drawing a custom envelope.
- **Automation (Green):** Creates dynamic changes over the event's duration, such as modulating frequency or amplitude to create more complex textures.
- **Buffer (Gray):** This module allows the effect currently in the 'Editing Buffer' to be copied into its own local buffer. From there, it can be saved to disk or triggered for playback by an external source (like a MIDI note or a 'bang' from a mapping module).

### A.1.3 Mapping Modules

These modules facilitate the connection between the DMI's controls and the haptic effects.

- **Filter (Light Purple):** Isolates specific control data. For example, it can be set to only pass MIDI CC #70, ignoring all other data.
- **Trigger (Pink):** A simple utility that sends a 'bang' (a trigger event) when an incoming value is greater than zero (e.g., "Press") and a separate 'bang' when it returns to zero (e.g., "Release").
- **Scale (Dark Purple):** The primary mapping module. It maps an incoming range of values (e.g., 0-127) to a new output range (e.g., 0.0-1.0 for amplitude). It also allows for setting discrete "Trigger Points" along the range, which send a 'bang' when the input value crosses them (e.g., to create 'detents' on a knob).

## A.2 Participant Background Questionnaire

**Table A.1** Participant Background Questionnaire

1. Do you play any musical instruments?
   Yes No
   If yes, please list them and indicate years of experience for each:
2. How would you rate your overall experience with Digital Musical Instruments (DMIs)?
   No experience Beginner Intermediate Advanced Expert
3. Have you ever designed or modified a DMI?
   Yes No
   If yes, please briefly describe:
4. How familiar are you with haptic feedback in technology?
   Not at all familiar Slightly familiar Moderately familiar
   Very familiar Extremely familiar
5. Have you ever used a device with vibrotactile feedback for musical purposes?
   Yes No
   If yes, please describe:
6. On a scale of 1-5, how important do you think tactile feedback is in musical instrument design?
   (1 being not important, 5 being very important)
   1 2 3 4 5
7. Have you had any experience with programming audio or haptic feedback?
   Yes No
   If yes, please describe:
8. Are you familiar with any of the following DMIs? (Check all that apply)
   Linnstrument Touché T-Stick None of these
9. Have you ever participated in a study involving DMIs or haptic feedback before?
   Yes No
   If yes, please briefly describe: